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3-D IMAGERY COCKPIT DISPLAY DEVELOPMENT

T.C. Way
R.E. Hobbs
J. Qualy-White
J.D. Gilmour

Boeing Military Airplane Company
P.O. Box 3707
Seattle, WA 98124-2207

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John Reising

JOHN M. REISING
Engineering Psychologist

RICHARD W. MOSS, Chief
Crew Systems Concepts Division
Cockpit Integration Directorate

FOR THE COMMANDER

Gene Smith

EUGENE A. SMITH, Col, USAF
Director
Cockpit Integration Directorate

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The 3-D Imagery Cockpit Display Development Program was designed to evaluate the potential payoff in situation awareness of adding retinal disparity (3-D) to pictorial formats for use in advanced aircraft and to advance the evolution of the pictorial formats themselves. The study consisted of designing the formats, evaluation of formats in part-task, part-mission, and full-mission simulation, and redesigning formats based on air crew feedback if needed.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAA	Anti-aircraft artillery
AFB	Air Force Base
AIM	Air intercept missile
BAS	Boeing Advanced Systems
BVR	Beyond visual range
CAP	Combat air patrol
CASS	Crew alerting and system status (format)
CLF	Close look format
CPA	Closest point of approach
CRT	Cathode ray tube
E-O	Electro-optical
EGT	Exhaust gas temperature
FIS	Fighter Interceptor Squadron
FLOT	Forward line of troops
HRL	Horizontal reference line
HSF	Horizontal situation format
HUD	Head up display
Hz	Hertz (cycles per second)
ID	Identification
IFFN	Identification friend, foe, neutral
IRST	Infra-red search and track
ITDL	Integrated Technology Development Laboratory
JTIDS	Joint Tactical Information Distribution System
K	Thousand
MLE	Missile launch envelope
MLE-O	Missile launch envelope - ownship
MLE-T	Missile launch envelope - threat
mm	Millimeter
MPD	Multipurpose display
ms	Millisecond
NADC	Naval Air Development Center
NAS	Naval Air Station
NM	Nautical mile
PSF	Perspective situation format
RF	Radio Frequency

LIST OF ACRONYMS AND ABBREVIATIONS (Cont'd)

Rmax1	Maximum launch range against non-maneuvering targets
Rmax2	Maximum launch range against maneuvering targets
Rmin	Minimum launch range based on missile arming and guidance
RMS	Root mean square
SAM	Surface to air missile
SWAT	Subjective Workload Assessment Technique
3-D	Three dimensional
2-D	Two dimensional
USAF	United States Air Force
USN	United States Navy
WRDC/KT	Wright Research and Development Center/Cockpit Integration Directorate

PREFACE

This report covers work accomplished by the Boeing Advanced Systems' (BAS) Crew Systems and Integrated Technology Development Laboratory (ITDL) Organizations for the Cockpit Integration Directorate of the Wright Research and Development Center under contract F33615-86-C-3601. Capt. John P. Zenyuh and later Capt. Ronald Opp were the Project Engineers, under the aegis of Dr. John M. Reising. Their guidance was important to the successful completion of the project.

The authors wish to specially acknowledge the contributions of the six Boeing pilots who flew in the status format test and the sixteen Air Force and Navy pilots who flew in the main simulation. These professional airmen brought their operational skills to bear and provided valuable information to the evolution of the formats. The Air Force F-15 pilots were from the 318th FIS, McChord AFB. Capt Bob Otto coordinated for the 318th. LCDR Rivers Cleveland and LCDR Phil Wheeler coordinated participation of the Navy A-6 pilots from NAS Whidbey Island. Navy participation was arranged through CAPT William F. Moroney of NADC. It is rewarding for a contractor to see interservice participation, particularly when it makes available such an able, interested, and articulate pool of subjects.

In Boeing Advanced Systems, the program manager was J. D. Gilmour, and principal investigator was T. C. Way. Other members of the BAS Crew Systems crew were: Roy Hobbs, who served as instructor pilot and worked on format revision; Robin Martin who was instrumental in the build-up phases and preparation for the simulation; and Judi Qualy-White, who designed the crew alerting and system status format and supported data collection.

The simulation was conducted in BAS's ITDL, a multipurpose, multiuser laboratory facility, managed by R. A. Becker. Laboratory personnel who contributed to the completion of the

project included Tony Alix, Bob Coyle, Al Dooley, Gary Douglas, Kevin McMahon, Eric Miyamoto, Vance Nielson, Jan Stevens and Steve Wagner. Farideh Mastan of Boeing Computer Services and Harold Mauldin of Boeing Advanced Systems assisted in data analysis.

EXECUTIVE SUMMARY

OBJECTIVES: A simulation program was undertaken to evaluate the potential payoff in situation awareness of adding retinal disparity (3-D) to pictorial formats for use in advanced aircraft and to advance the evolution of the pictorial formats themselves.

BACKGROUND: The complexities of modern aircraft and their projected missions threaten to overcome aircrews with information and tasks. Advances in display and information processing technologies have yielded degrees of freedom which are available to display designers to help overcome the cockpit information glut. Earlier contracts in this series have studied the use of color and pictorial formats. The current study explored one more of those advances - the application of stereopsis to pictorial display formats.

APPROACH: The strategy in this effort was to break the family of display formats into two groups: those which relate primarily to aircraft systems and those which relate to the mission and its environment. The systems formats were represented by two examples: sensor coverage and electrical system status. The former was a "wire globe" shape with an embedded airplane. The parallels and meridians of the globe divided it into sectors of sensor coverage. The electrical system status format was a high level schematic diagram of the electrical system. Application of stereopsis to these two formats was evaluated with a part-task response time paradigm. Six former military pilots participated.

Application of stereopsis to the mission and environment formats was evaluated in the context of simulated air-to-air and air-to-ground missions. These formats included the HUD, a perspective situation format, a horizontal situation format and a close-look format used in the air-to-air missions. Sixteen operational

fighter or attack pilots participated, two at a time, in the four day training and test program. There was an attempt to collect operationally meaningful performance measures in these simulations. Workload and opinion data were collected, as well.

RESULTS AND CONCLUSIONS: In the status format test, stereopsis reduced both response time and errors when it was applied to the sensor coverage format, but not to the electrical status format. It was concluded that stereopsis is beneficial when it is applied to augment monocular depth cues, but that it is not as effective as differential color when used for attention getting.

In the main simulation study, stereopsis was not found to significantly affect performance or workload. Although all of the pilots perceived the stereo effect, they did not generally support use of stereo in the cockpit displays. This may have been impacted by the fact that they associated stereo with a resolution penalty and would have preferred the resolution.

The pilots generally found that the pictorial formats satisfied their information requirements. Among them, they suggested a number of improvements, some of which have been incorporated into a second version of a head up display, perspective situation formats, horizontal situation format and crew alerting format.

1.0 INTRODUCTION

This document is the final report prepared by Boeing Advanced Systems under the 3-D Imagery Cockpit Display Development Program, Contract F33615-86-C-3601.

1.1 Background

The increasing complexities of modern weapon systems and missions are placing demands on aircrew that often exceed their ability to perform in the traditional manner. Advanced avionics and supporting ground systems are capable of collecting, processing, and distributing unprecedented amounts of operational data, much of which is essential in order to cope with current and projected mission requirements and threat situations. At the same time, the air vehicle, subsystems, and weapons are themselves becoming more sophisticated in order to support extended performance goals including beyond-visual-range (BVR) operating conditions. As a result, crews are being faced with much more information to interpret, more complex instructions to give their onboard systems, and considerably less time to perform these functions. Desired performance gains associated with new weapon systems may not be achieved if these requirements exceed the aircrew's ability to perform the necessary tasks in a timely manner.

Historically, aircrews have been able to function successfully at an operator level, exercising direct monitoring and control over many of the individual components and subsystems that comprise the total weapon system. In this capacity, the crews effectively performed their information fusion in real time. Using essentially raw data, crews were required to search, monitor, interpret, transform, integrate, and evaluate multiple readouts in order to arrive at the alternatives, decisions, and control actions needed to manage the aircraft and mission. Raw data for this purpose was most typically obtained from dedicated electromechanical instrumentation in alphanumeric or analog form. In the current complex environment this approach is no longer feasible; it has become clear that the information processing capacity of man can severely limit the overall performance of the system. Modern efforts toward cockpit integration are dramatically enhancing the role of the crew, allowing them to more effectively exercise appropriate aircraft and mission control functions at a management level.

Technology that has resulted in increased complexity has simultaneously created some of the advances needed to solve the problem. Rapid advances in computing and data processing technology have made it possible to automate many of the raw data functions previously performed manually, thus offering the aircrew processed decision-level information tailored to management responsibilities. Mass storage and high speed processing also provide the potential for more and better systems and mission information available to the crew than they could hope to achieve manually, as well as the means to help determine what information is needed and when. Multifunction electro-optical displays and controls have given the crewstation designer and the pilot vastly increased levels of flexibility in the cockpit. The flexible programming offered by these devices allows for the true integration of information and control functions according to the needs of the crew, and for the rapid reconfiguration of the cockpit based on changing mission and system conditions. The numerous readouts of alphanumeric raw data can thus be replaced by integrated, mission oriented displays formatted for ease of interpretation, heightened situational awareness, and rapid decision-aiding.

Until recently, the advantages of programmable electro-optical displays and controls, including the use of color and graphic or pictorial information, have only been partially exploited. Although the flexibility exists, there has only infrequently been an examination of aircrew information needs together with the formats and symbology best able to convey the information. Instead, there has been a tendency to mimic the appearance of electromechanical instruments. One of the prime goals of this program series is to extensively explore the concept of replacing the alphanumeric data typically used in the past with integrated graphic and pictorial display formats.

1.2 Previous Work

This is the fourth in a series of contracted efforts, sponsored primarily by the Air Force Flight Dynamics Laboratory, Crew Systems Development Branch, (AFWAL/FIGR). In the first of these efforts, conceptual displays were developed for six primary fighter crew station functions: primary flight, tactical situation, stores management, systems status, engine status, and emergency procedures (Jauer and Quinn, 1982).

In the second contract, Pictorial Format Display Evaluation, Boeing continued the development beyond the paper formats of the earlier program and implemented the results in a piloted simulation. Two simulation studies were conducted to evaluate the usability and acceptability of pictorial format displays for fighter aircraft; to determine whether usability and acceptability were affected by display mode -- color or monochrome; and to recommend format changes based on the simulations.

In the Basic Pictorial Display Evaluation Study, pictorial formats were implemented and evaluated for flight, tactical situation, system status, engine status, stores management, and emergency status displays. In the Threat Warning Study, the number of threats and the amount and type of threat information were increased. This second evaluation concentrated on depiction of threat data. These two studies were published in the second report of the series (Way, Hornsby, Gilmour, Edwards and Hobbs, 1984).

The next study was called the Multi-Crew Pictorial Format Display Evaluation Program. In it, two-member crews flew low level penetration, system health, and beyond visual range air to air missions. They evaluated the evolving display formats (Way, Martin, Gilmour, Hornsby and Edwards, 1987). A total of sixty-two USAF and USN pilots and weapon system officers in the three studies flew mission simulations with color and monochrome versions of the displays. Objective performance data, workload data, pilot ratings, and comments were collected. In general, the pilots found the pictorial format displays, and the specific implementations used in these studies to be quite acceptable. They preferred color over monochrome versions. A number of improvements were suggested for particular format elements, and were incorporated into revised formats. The formats in this simulation have benefitted from these previous iterations.

1.3 Objectives of This Study

The present study had two primary objectives. One was to evaluate usability and pilot acceptability of the formats as they have evolved through the continuing development programs. The second objective was to evaluate the potential payoff in situation awareness of adding a true third dimension to the 2-D pictorial formats. The formats evaluated were derived from the earlier work and were significant advances.

It is intended that the results of this study will support the Services in their efforts to provide a firm technology base in the area of aircraft crew stations and displays and controls. In addition, the work will support the Air Force Armament and Avionics Laboratories in their respective goals of developing integrated stores management and avionic systems that are compatible with advanced crew interface concepts and workload requirements. These service goals are being pursued through a number of exploratory and advanced development programs that include the demonstrated feasibility of cockpit electro-optical (E-O) displays driven by high speed digital computers. This program will further these objectives by simulating and evaluating a representative set of E-O display formats that have been designed to significantly reduce the information processing demands placed upon pilots. This reduction in mental workload will allow pilots to extract information from the cockpit and conduct the mission in a more efficient manner.

Maintaining internal and external situation awareness in future combat situations is a key factor in achieving mission success. One means of providing this situation awareness is through use of two-dimensional (2-D) perspective, color pictorial displays. It is now technologically possible to add stereopsis or retinal disparity to these formats, thus providing an added cue to depth. The goal of the current contract was to evaluate the potential payoff in situational awareness of adding 3-D information in this way. Specifically under evaluation are the applications of retinal disparity to the flight formats, tactical situation formats, and systems status formats.

1.4 Research Strategy

The primary flight displays are the head-up display on the upper CRT, the perspective situation format and close-look format which share the center CRT and the horizontal situation format on the lower CRT. These were tested in the main simulation study. The status formats on the left and right CRTs were represented in the status format test. The cockpit arrangement is detailed in Figure 3.2-1.

There are two basic applications of stereo to these status formats. One is to enhance conspicuity of some display element on a format to which we want to draw the pilot's attention. The second is to augment other depth cues in a picture of a three-dimensional object. Among the status formats were two which allowed clean tests of these two applications. These were tested using a part task simulation in the status format test and represented the class of status formats.

1.5 Organization of This Document

Section 2 of this report describes some of the theory and findings which led to this application of stereopsis as a 3-D effect in cockpit displays. Section 3 describes the test equipment and facilities employed here including a description of the simulated aircraft and the cockpit. Section 4 discusses specific systems of the aircraft and the display formats that were used with those systems. The formats displayed both normal conditions and system health problems. Section 5 presents the procedures used in response to these problems and the formats which outlined the procedures. Section 6 describes the status format test. Section 7 provides information on how the main study was conducted. The schedule and mission briefing information are presented together with a description of the data that was collected. Section 8 gives results of the main study and, finally, Section 9 presents conclusions and recommended format revisions.

2.0 3-D EFFECTS

There are a number of cues to depth used by computer graphics designers. These include perspective, interposition, rotation, relative size, and shading. When we view real-world objects, we have the additional physiological depth cues of accommodation, convergence and lateral retinal disparity. Accommodation is the change in shape of the lens of the eye when we focus on objects at different distances. Convergence is the crossing and uncrossing of the two eyes as we fixate at different distances. Lateral retinal disparity is the location of objects from different distances at different relative positions in the two retinal images. Approximately 90 percent of the population can fuse the two images into one and perceive the disparity as depth. This perception is called stereopsis and the ability to perceive depth in this manner is called stereoacuity.

Figure 2.0-1 illustrates stereopsis as a depth cue. If the two eyes are fixated on point "F", their lenses are shaped to hold that point in focus. The lenses would change shape to focus closer to fixate "N". This effect is accommodation. Similarly, compared with a fixation at "F", the eyes would converge or cross to fixate "N". On a CRT display surface, unlike normal real-world viewing, accommodation and convergence are fixed and determined by eye-to-screen viewing distance. They cannot be manipulated to create 3-D effects.

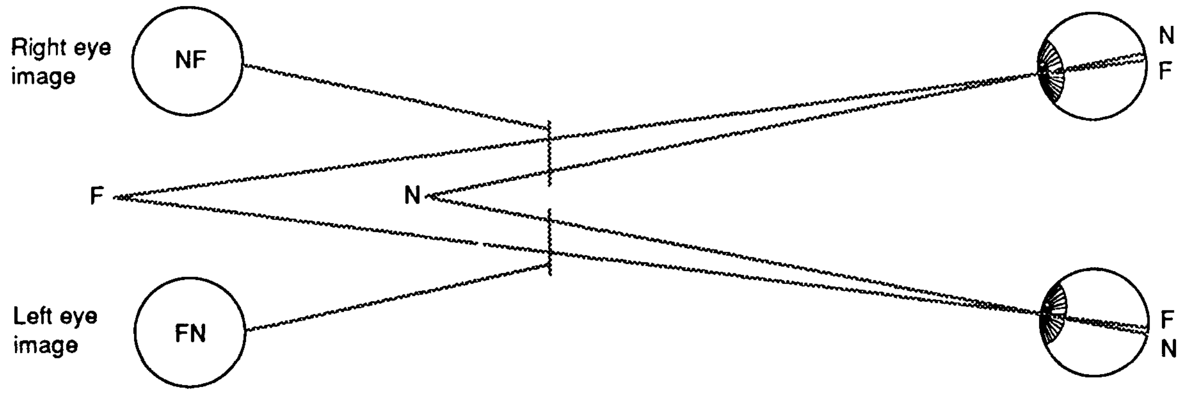


Figure 2.0-1. Lateral Disparity as a Depth Cue

Stereopsis, however, can be manipulated by creating the disparate left- and right-eye images and presenting them to the appropriate eye. In this program, stereopsis was added to the video images by creating left- and right-eye subfields and time-multiplexing them in the manner described in Section 3.

3.0 TEST EQUIPMENT AND FACILITIES

The simulations used in this study were created with a subset of the facilities comprising Boeing Advanced Systems' (BAS) Integrated Technology Development Laboratory (ITDL). The ITDL is a new two-story, 104,000 square foot, multipurpose, multiuser capital facility designed from the ground up to support contract projects and Boeing research and development activities. The scope of the laboratory includes full computational resources for flight simulation, multipurpose engagement simulation, sensor display simulation, digital avionics, digital flight controls, and artificial intelligence to complement three simulation domes and a six degree-of-freedom motion base simulator. All laboratories are integrated through a common high-speed fiber optic network. Discussed here are the resources which were assigned for the accomplishment of the 3-D Imagery Cockpit Display Development work.

3.1 Simulation Architecture and Display Generation

Figure 3.1-1 is a schematic diagram of major simulation elements and their arrangement. A Gould SEL 32/9780 computer and a Star Technologies ST-100 array processor performed real-time modeling of airframes, navigation cells, and control systems, supplied graphics subsystem data, and provided on-line data recording. An F-15 tactical fighter model, a real world coordinate navigation cell, and a flight-display control program provided both closed loop and automatic flight modes. Adversary aircraft and airborne missiles were also modeled in the host computers.

The digital simulation data were passed through a 10 MHz serial ProNet digital data bus comprised of one bus controller connected through an interface to the Gould SEL 32/9780 computer and two fiber optic modem units. These units transparently interconnected the wire buses. Two bus interface controllers were connected via memory buffers to the crew station input/output system, and the Gould SEL 32/6780 graphics

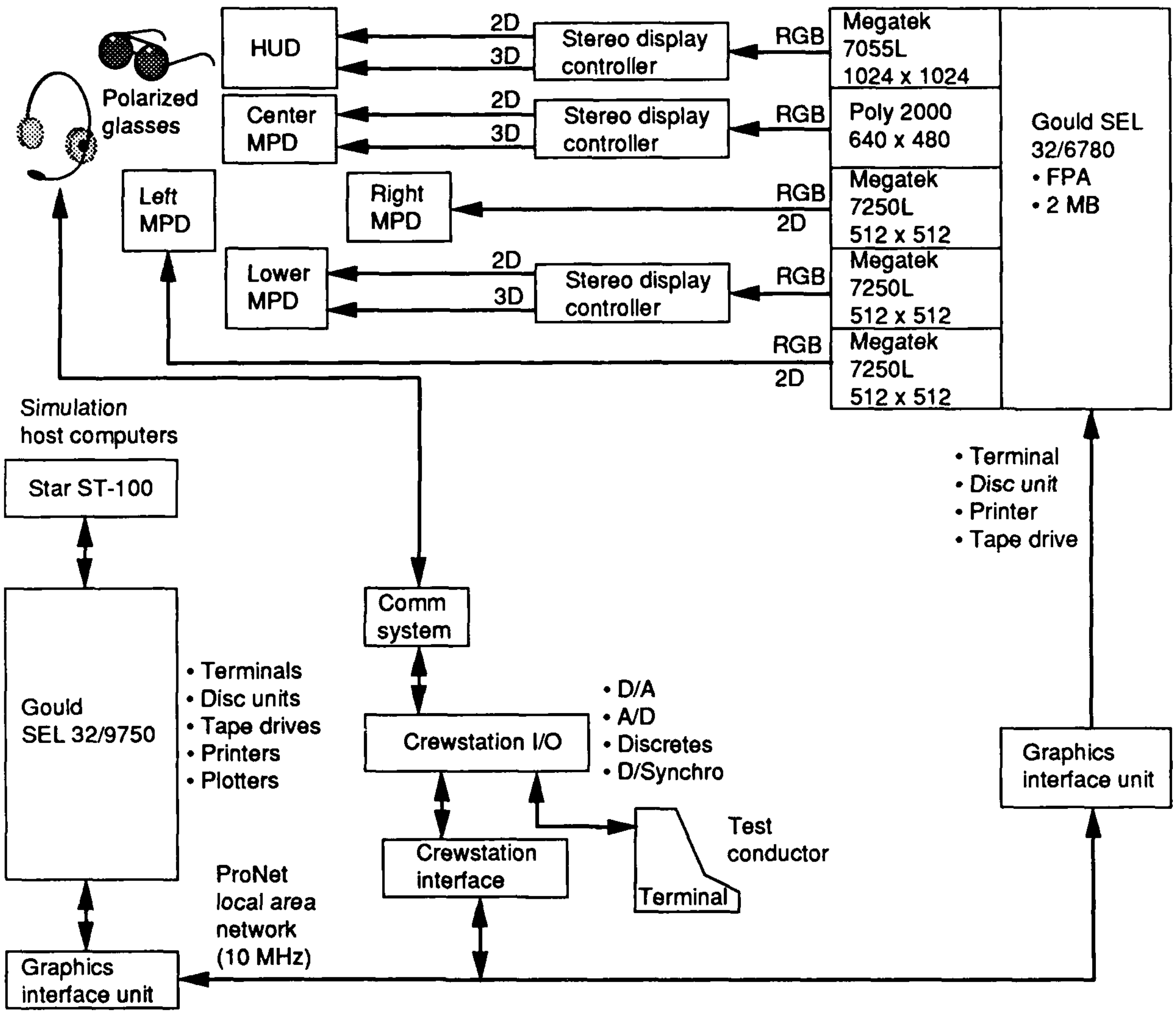


Figure 3.1-1. Schematic Diagram of Major Simulation Elements

generation computer.

Supported by the dedicated Gould SEL 32/6780, the graphics generators accepted data from the host computers, generated the display formats, and updated them to reflect pilot input and progress of the mission. Status formats on the left and right multipurpose displays (MPD) were generated by the two channels of a dual-channel Megatek graphics generator. The HUD was generated by a Megatek 640-line system and the Horizontal Situation Format (HSF) by another Megatek. On the center MPD, the Close Look Format (CLF) and the Perspective Situation Format (PSF) were generated by a GTI Poly 2000 640-line system. The latter four formats - HUD, HSF, CLF and PSF - were treated for the 2-D versus 3-D comparison using Stereographics display controllers. For those formats, the display generators created left- and right-eye images which shared the available display generator scan lines. Then, by alternating between the left- and right-eye subfields at 120 Hz and simultaneously changing the polarity of the LCD polarizing screens, the left and right images were presented through polarized glasses to the pilot's eyes. The process was under software control by making the two images coincident in the 2-D case and selectively adding disparity in the 3-D case. The pilots wore polarized glasses in both cases. This part of the process is illustrated in Figure 3.1-2.

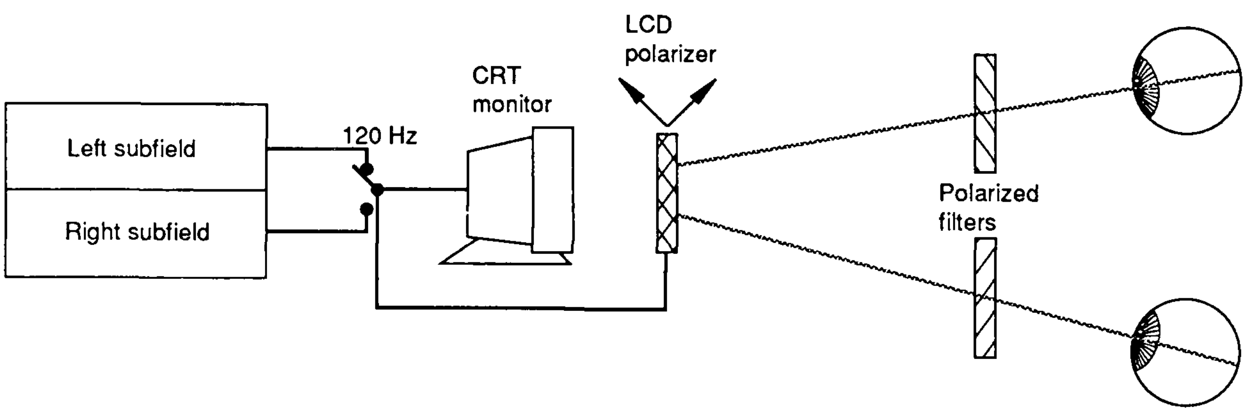
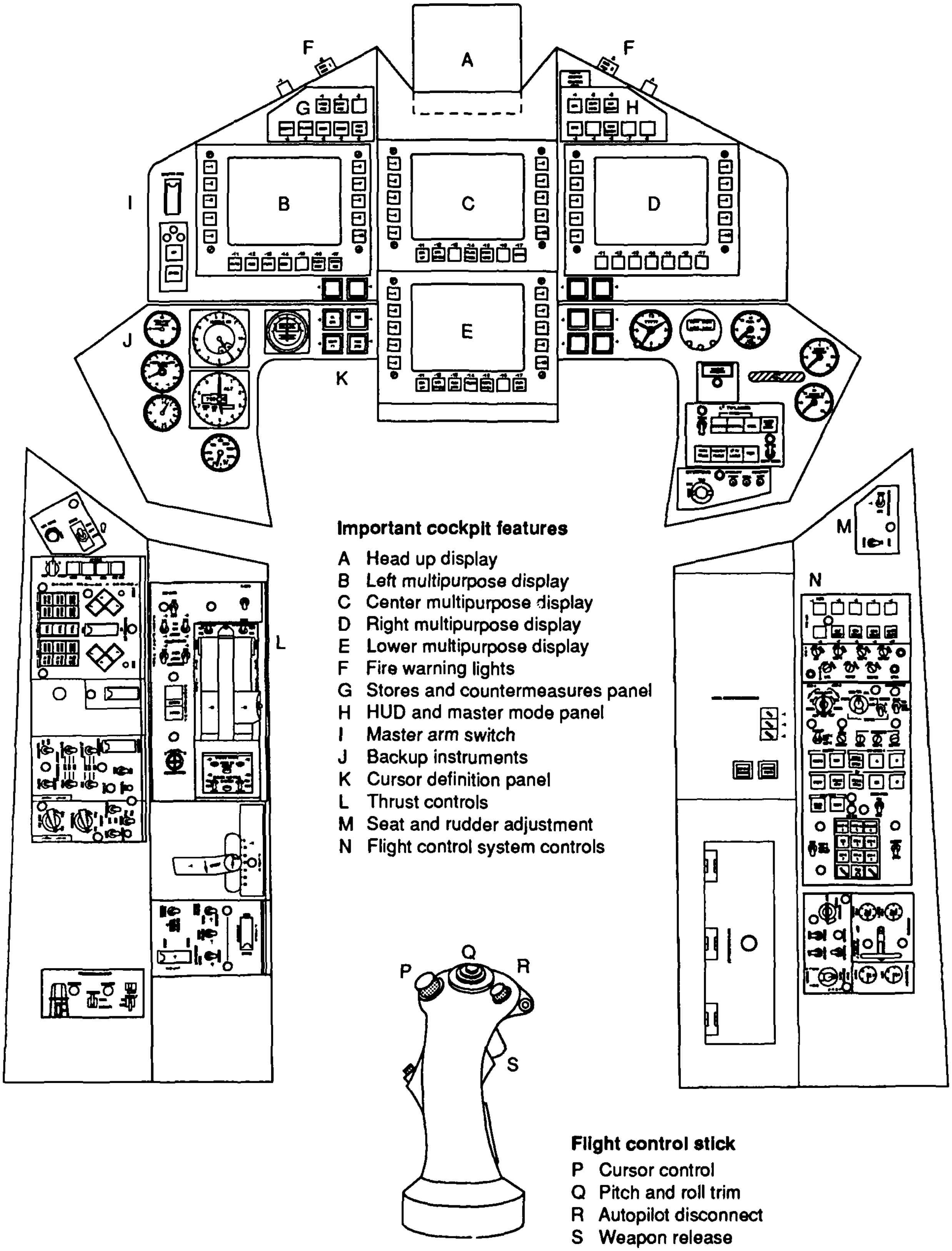


Figure 3.1-2. Raster Scan Stereo Display System

3.2 Layout of the Fighter Cockpit

The vehicle for this test represented a multipurpose fighter/attack aircraft of the mid-1990's time frame. The aerodynamic characteristics were similar to the F-15. The aircraft was powered by two high performance turbofan engines with afterburners. Primary armament was tailored to the airplane's two roles. In the air-to-ground missions it carried a gun, two anti-radiation missiles, and two guided bombs. In the air-to-air missions it carried the gun, two short range, heat seeking AIM's and four long range, radar guided missiles.

The simulated cockpit was designed to support a dual role mission. There were some back-up instruments but the primary display suite consisted of a HUD and the four multipurpose displays. Controls for managing these displays were grouped around them on the forward panel. Figure 3.2-1 shows the major display and control areas which were used in this study. These are detailed in the following sections. Note that the extreme hands-on-stick-and-throttle concept was deliberately not implemented here. However, an attempt was made to group frequently used controls on the left to leave the right hand free for the flight control stick.



Important cockpit features

- A Head up display
- B Left multipurpose display
- C Center multipurpose display
- D Right multipurpose display
- E Lower multipurpose display
- F Fire warning lights
- G Stores and countermeasures panel
- H HUD and master mode panel
- I Master arm switch
- J Backup instruments
- K Cursor definition panel
- L Thrust controls
- M Seat and rudder adjustment
- N Flight control system controls

Flight control stick

- P Cursor control
- Q Pitch and roll trim
- R Autopilot disconnect
- S Weapon release

Figure 3.2-1. Cockpit Arrangement

4.0 AIRCRAFT SYSTEMS AND FORMATS

This section details the specific aircraft systems used in this simulation, together with the formats which served them. There were a number of systems without an associated format and others were represented in integrated formats. Each is discussed in turn.

4.1 Flight Control System

Flight controls operated in the conventional manner. Hydraulically actuated surfaces controlled the aircraft in three axes. In-flight speed brakes were available, controlled by a switch on the inboard throttle handle.

4.1.1 Manual Controls

The control stick was hydraulically operated and included a force feel system. Pitch and roll were controlled by the stick; pitch and roll trim were controlled by the trim switch on the stick. Yaw was hydraulically controlled with the rudder pedals which were adjustable for pilot comfort.

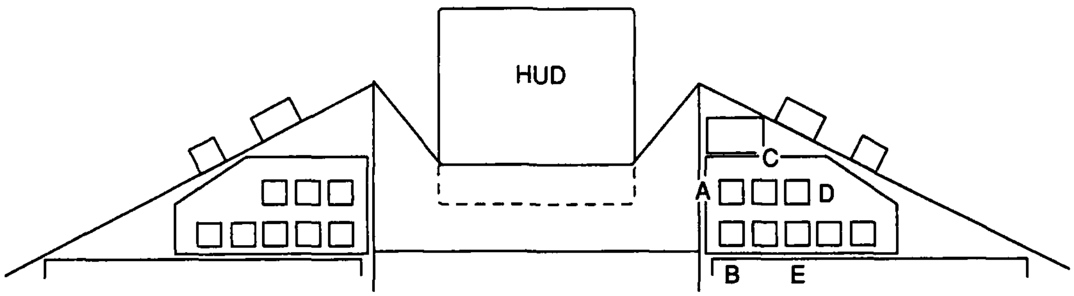
4.1.2 Automatic Flight Control System

The aircraft had a three channel autopilot. The option to independently select airspeed hold, heading hold, or altitude hold was also available, with selection of one of the switches of the right side panel. The combined autopilot was selected with either the autopilot button on the right side panel or the autopilot control switch on the stick. When engaged, the autopilot maintained current altitude, airspeed, and heading.

4.2 Display System

Display formats were distributed across five CRT displays. The formats are discussed in subsequent sections. The HUD was the primary flight display. The four multipurpose displays are referred to as the left, center, right and lower MPD's. The Perspective Situation Format (PSF) and the Close Look Format (CLF) time-shared the center MPD. The lower MPD was the site for the Horizontal Situation Format (HSF). Status formats for the electrical, engine, fuel, hydraulic, sensor, and stores/countermeasures systems were each pilot selectable on the left MPD. The right MPD always contained the Crew Alerting and System Status (CASS) format. The HUD as well as the center and lower MPD's were treated for an added 3-D effect. In selected flights, the formats appearing on these displays had retinal disparity added - the augmented cue to depth. Lighted push button switches were operational with each of the formats, with the single exception of the right MPD's format. The switches had three states: bright for "on", green for "available", and no visible legend for "not available".

A number of display features were defined by selection of master mode - air or ground. Master mode controls shown in Figure 4.2-1 affected the Head-Up Display, the Perspective Situation Format, and the Horizontal Situation Format. For the HUD, missile launch envelopes (MLEs) were displayed only when in air mode. For the PSF, the display features and displayed threats



Legend:

A Coupled navigation mode
B Manual navigation mode
C Vertical velocity indicator
D Master air mode
E Master ground mode

Figure 4.2-1. Master Mode Controls and HUD Options changed substantially with the different missions. In ground mode, only surface threats were shown; in air mode only airborne traffic were displayed. Similarly, the HSF generally displayed surface threats or airborne traffic as a function of the selected master mode. In addition, master mode selection determined which of the onboard weapons were appropriate and available.

4.2.1 Head-Up Display

The Head-Up Display (HUD) was the primary flight instrument. It contained flight attitude and guidance information and specific cues to warn the pilot that attention to other displays was required.

4.2.1.1 Head-Up Display Format Description

An example of the basic HUD format is shown in Figure 4.2-2. The pathway (A) showed the planned route and provided flight

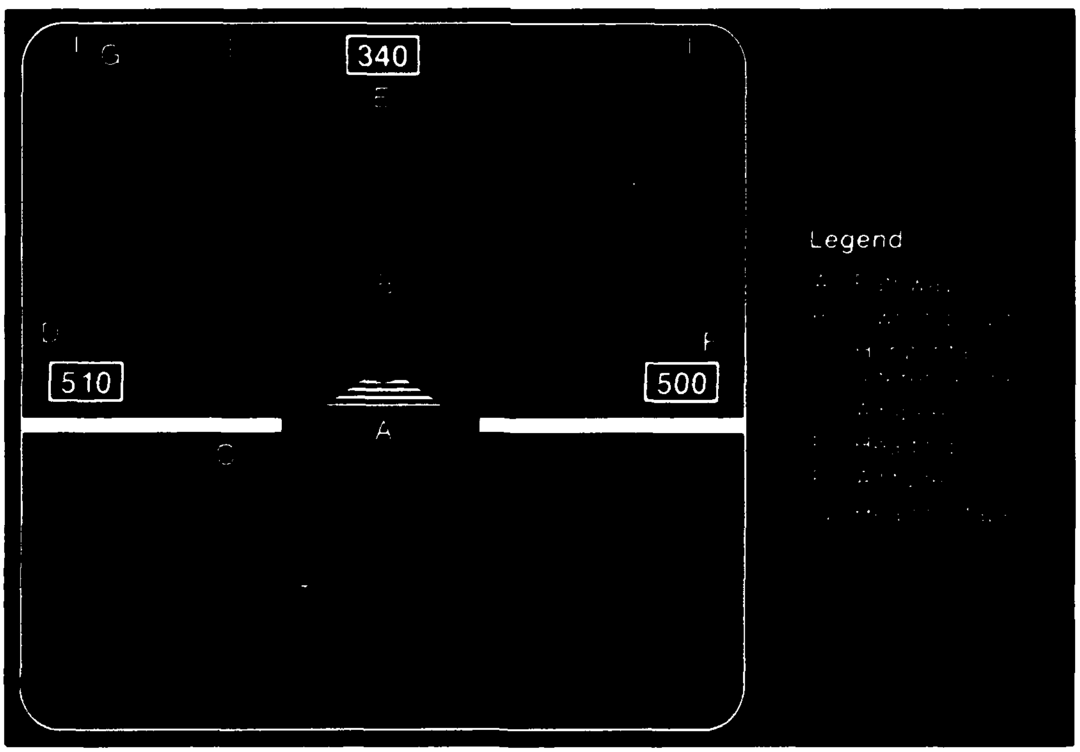


Figure 4.2-2. Head-Up Display

director information. The pathway was composed of a series of segments, alternately white and transparent. Each segment, white or transparent, represented a length of 1000 feet and a width of 300 feet. The bottom of the pathway's white segments had superimposed cyan chevrons to distinguish it from the top. The cyan ownship symbol (B) represented a velocity vector which, at the airspeeds simulated, was essentially centered in the display. With ownship on course, the pathway was centered about the ownship symbol, and the wings on either side of the front of the pathway were aligned with the wings of the ownship symbol. If ownship was off course, the pathway was displaced relative to the ownship symbol. For example, if the pathway was above and to the left of the aircraft symbol, it indicated that the pilot should pull up and turn to the left in order to return to the planned course.

The horizontal reference line (HRL) indicated the aircraft's orientation relative to the earth at any attitude. In straight and level flight the HRL (C) appeared as a pair of solid lines extending from either side of the ownship symbol. For pitch up, a pair of 'feet' were attached to the HRL and pointed down toward the horizon; for pitch down, the 'feet' of the HRL pointed up toward the horizon. The HRL overlaid the true horizon when it was in the field of view. At more extreme pitch angles, the HRL pegged at the top (for pitch down) or bottom (for pitch up), thereby continuing to provide roll information with an immediate indication of direction back to level flight.

Terrain within the field of view and the ground plane were displayed on the HUD. The HUD included digital readouts of airspeed (D), heading (E), and altitude (F) at the left, top, and right of the display, respectively. A heading tape (G) was displayed in conjunction with the heading readout. A row of short vertical lines 5° apart, formed the heading tape.

Commanded changes in a parameter were shown by a solid cyan arrow, attached to the digital readout box indicating the direction of the change (up or down for altitude and airspeed; left or right for heading). The commanded value was shown next to the arrow.

The HUD provided symbolic threat alert and summary symbols for threats in track or launch/fire mode. Alert information appeared in a position directly beneath the ownship symbol; summary information was displayed in a row beneath the alert position as required. An anti-aircraft artillery (AAA) site was represented by a gun shaped symbol, a surface-to-air missile (SAM) site by a missile shaped symbol, and an airborne threat by an aircraft symbol.

For threats in track mode, the appropriate symbol, coded amber appeared in the alert position for six seconds and then shifted to the summary line. A symbol remained in the summary line throughout the track condition, returned to the alert position upon transition to the launch/fire condition; it was deleted with effective ownship countermeasures, i.e., lock is broken. If more than one threat was in the track condition, the total number was indicated digitally beneath the appropriate symbol. The total number of threats tracking ownship excluded that symbol which may appear in the alert position.

For threats in launch/fire mode the appropriate symbol was coded red and appeared in the alert position for the duration of missile flight (SAM or air-to-air) or AAA firing. Missile or AAA site azimuth was shown by the position of a red vector radiating from the ownship symbol. For SAM's and air-to-air missiles, a countdown to estimated missile impact (seconds) and the missile seeker type (radar or infrared) was displayed alongside the alert symbol. Both the threat azimuth vector and the time to impact readout were displayed as long as the incoming missile was in flight and locked on. If lock was broken, these were deleted.

In addition to the threat alert and summary information, for the primary airborne threat and/or target, the instantaneous missile launch envelope (MLE) of ownship and enemy missiles was presented whenever ownship or a target was being tracked or launched against (Figure 4.2-3). MLE information was shown by two vertical arrows, one on the left side and one on the right side of the display. The attack arrow to the left pointed up and represented the current capability of ownship's selected missile against the targeted aircraft. The defensive arrow to the right pointed down and represented the assumed current capability of adversary missiles against ownship. The MLE was determined as a function of relative altitude, closing velocity, and relative azimuth.

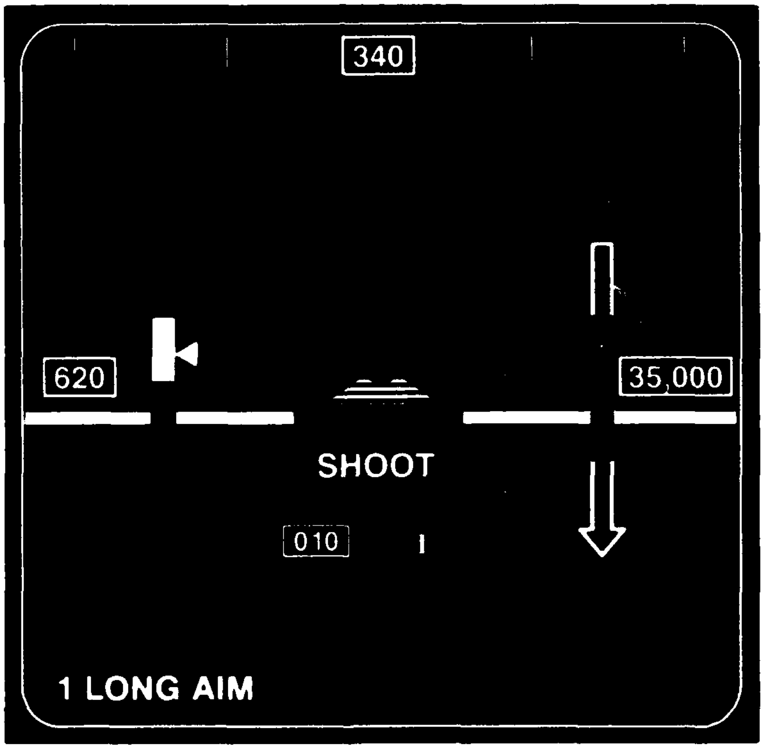


Figure 4.2-3. Head-Up Display Threat and MLE Symbology

Each of the MLE arrows was divided into four color coded sections. The bottom section of each arrow represented a range greater than Rmax1. The next section, from Rmax1 to Rmax2, displayed the approximate Rmax (maximum range) for onboard radar guided air intercept missiles (AIMs) against the current designated target and was coded green along the attack arrow; amber along the defensive arrow. The next section up on each arrow, from Rmax2 to Rmin, displayed the approximate band of no-escape ranges for onboard AIMs against the current designated target and was coded white along the attack arrow; red along the defensive arrow. The top section of each arrow represented a range below Rmin, i.e., less than the minimum arming and launching range of the missile. Thus, the arrows and their sections were color coded as follows: The attack arrow was outlined in cyan, and its four sections, from bottom to top were filled with black (greater than Rmax), green (Rmax), white (no-escape) and black (less than minimum). The reason for this order of green and white coding was consistency with the other formats. The defensive arrow was outlined in white, and its four sections from bottom to top were filled with black (greater than Rmax), amber (Rmax), red (no-escape) and black (less than minimum).

The range of the primary target (or threat) relative to ownship's missile was shown by the position, movement, and color of a caret which moved along the attack MLE. As ownship and the target maneuvered such that ownship's range to the target progressed from Rmax1 through Rmax2 and into the no-escape section of the arrow, the caret moved up along the arrow, from bottom to top. Conversely, when ownship's missile range to the target deteriorated, the caret moved toward the bottom of the arrow. The color coding of the caret reflected the color coding of the adjacent MLE section. Similar positioning and movement rules held for the position of the caret along the defensive MLE. As the attack and defensive MLE were shown for the primary target (or threat) only, each MLE possessed only one caret.

When a weapon was targeted by the pilot, the number and type of the weapon was given in white in the lower left corner of the HUD. If the pilot had not fired and all weapon release parameters were met, i.e., the master arm was on, the weapon had been selected and targeted, and the targeted aircraft had reached Rmax2, the word SHOOT appeared in white under the ownship symbol. When the pilot handed off the weapon to the weapon release system (by using the trigger on the flight control stick), the SHOOT cue vanished.

4.2.1.2 Head-Up Display Options

HUD options (shown in Figure 4.2-1) available to the pilot included the pitch ladder and a vertical velocity indicator. The pathway could be replaced with a pitch ladder if the pilot chose to exercise the manual navigation mode (4.2.4 Navigation). A vertical velocity indicator (with digital readout) could be added to the upper right corner of the display by using the VERT VEL switch.

4.2.1.3 3-D Features of the Head-Up Display

In the HUD 3-D display condition, parallax was used to model depth as a function of *range from ownship* and was added to a number of symbols as a secondary warning component. The 3-D model reference was the ownship symbol, which appeared at the display plane. Features of the HUD viewed forward of the aircraft, such as the pathway and terrain were modeled with continuous positive disparity. Thus, the pathway and the visible terrain appeared to recede beyond the display plane. The greater the range of a pathway segment or an individual mountain from ownship, the greater the recession from the display plane. Maximum parallax was 7.4 mm or 33.4 minutes of uncrossed disparity at the 762 mm viewing distance. This limit was reached for objects at 20 NM away.

The HUD airspeed, heading, and altitude readouts were coded amber or red in the event of a system malfunction or failure. In addition, discrete negative disparity was added to the readouts such that each appeared to protrude from the display surface. Threat alert and summary symbols, when displayed also appeared with discrete negative parallax as did the shoot cue.

4.2.2 Perspective Situation Format

The Perspective Situation Format (PSF) gave a perspective view of ownship, the planned route, terrain, and the threat environment. The information was correlated with its plan view counterpart on the Horizontal Situation Format. The viewpoint of the display was one mile behind and one thousand feet above ownship.

4.2.2.1 Perspective Situation Format Description

An example of the Perspective Situation Format, in ground mode, is shown in Figure 4.2-4. Ownship was represented by a cyan aircraft symbol in the center of the display (A). A small cyan pyramid (B) marked the ground position over which ownship was flying. The planned flight route was composed of a series of white triangles pointing in the direction of the flight route (C). Waypoint locations were shown by numbered flags on the pathway. Terrain was represented as a three dimensional surface with mountains. Terrain above current ownship altitude was

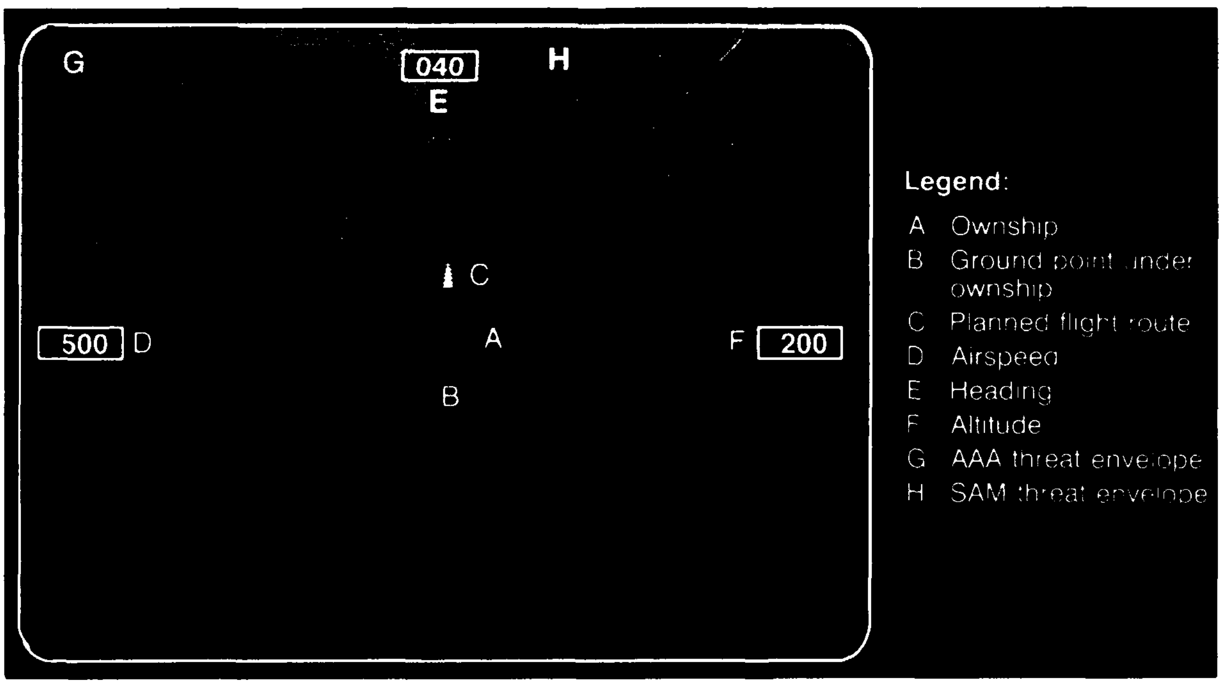


Figure 4.2-4. Perspective Situation Format, Ground Mode

brown; terrain below current ownship altitude was green. A green on green pattern of one-mile squares overlaid the ground plane. As the pattern became smaller, approaching and converging on the horizon, it gave a perspective effect to the terrain. Readouts of airspeed (D), heading (E), and altitude (F) were shown at the left, top, and right of the format, corresponding with the HUD.

Threat type, location, mode, and lethality area were displayed on the PSF. Active surface-to-air threats (SAMs and AAAs) were represented by threat lethality volumes. AAA threat volume (G) was red; a red footprint overlaid the ground plane area enclosed by the threat volume, and a gun symbol marked the actual AAA location. A SAM had two lethality volumes: the inner area was red, surrounded by an outer area of amber, to represent areas of higher and lower lethality. A red and amber footprint indicated the ground coverage of the SAM and a missile symbol marked the actual site location.

As a threat transitioned to track mode, an amber tractor beam connected the threat site to ownship and an amber lock-on ring enclosed ownship. In launch or fire mode, the tractor beam and lock-on ring were coded red. In addition, for SAMs, a round red missile symbol marked the current position of the missile, absorbing the tractor beam as it approached ownship. If ownship's countermeasures were effective, the tractor beam and lock-on ring vanished. With an ownship launch upon a threat, a cyan missile symbol was added to the display, indicating missile position as it approached the threat.

The symbology which formed the air mode PSF was based on a segment of a circular cylinder and was composed of the ground grid, segment axis, altitude verticals, and altitude ceiling (Figure 4.2-5). The air mode segment (coded white) displayed $\pm 45^{\circ}$, representing ownship radar coverage azimuth limits and a radar range of 120 NM forward of ownship. The ground grid was composed of 10° radials and range arcs 10 NM apart, forming the

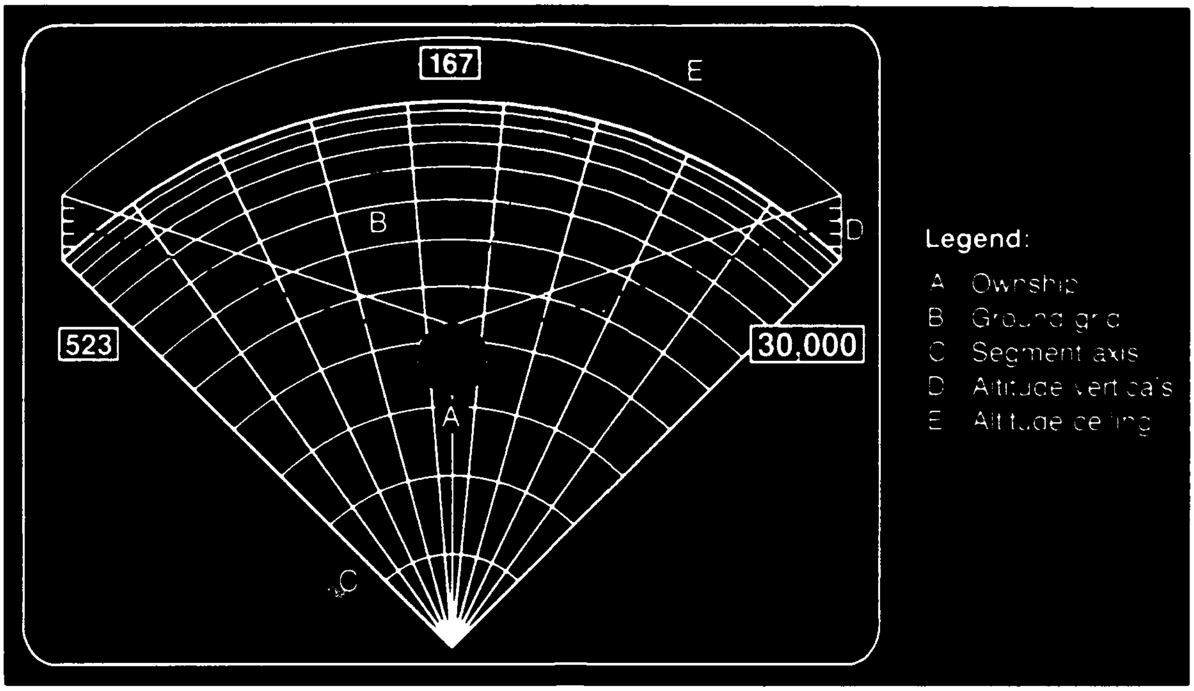


Figure 4.2-5. Perspective Situation Format, Air Mode

bottom of the cylinder segment. The radials converged at the origin of the segment axis. The two altitude verticals extended from the ground plane (at the -45° radial, 120 NM and at the +45° radial at 120 NM) to the top of the segment. The altitude verticals, forming the sides of the segment were marked at intervals of 10,000 feet. The altitude ceiling at 50,000 feet was represented by a range arc at 120 NM, connecting the altitude verticals.

Ownship was centered in the display, along the segment axis. When the radar was active, its azimuth limits were drawn as a pair of cyan lines from ownship to the altitude vertical. The points where the radar lines intersected the altitude verticals were connected by a cyan range arc at 120 NM. The radar lines and arc reflected changes in ownship altitude as they moved along the altitude vertical. The ownship symbol however, remained fixed along the segment axis.

Detected, track mode, and launch mode aircraft were displayed within the PSF. Detected aircraft symbols were coded red to represent threat aircraft, amber for unknowns, and green for friendlies. Each symbol possessed a short vector indicating aircraft heading. The aircraft and its attached vector always pointed in the direction of flight. Aircraft displayed within the air mode segment were attached to vertical lines, which extended from the ground plane. The height of the vertical line represented of aircraft altitude. The origin of the vertical line represented aircraft range and bearing from ownship.

Should an aircraft begin to track ownship, an amber lock-on ring enclosed ownship, and an amber tractor beam connected the aircraft to ownship. In launch/fire mode, the lock-on ring and tractor beam were coded red. For inbound missiles a red missile shaped symbol was added which showed the current position of the missile. The missile symbol absorbed the tractor beam as it travelled toward ownship. If lock was broken in track or launch mode, the tractor beam, and lock-on ring vanished. With an ownship launch upon a threat, a cyan missile symbol was added to the display, indicating missile position as it approached the threat.

4.2.2.2 3-D Features of the Perspective Situation Format

As in the HUD, the ownship symbol of the PSF was fixed at the display plane. Elements or objects beyond ownship receded into the display - the result of positive disparity. Display elements which intervened between the ownship symbol and the view point (6,000 feet aft and 1,000 feet above ownship) protruded from the display - the result of negative disparity. Thus, ground mode features of the format, terrain and threat envelopes for example, which were displayed at maximum range (30 NM), possessed the maximum positive disparity. As range to the features decreased, the disparity decreased proportionally. At the ownship display plane, range from a particular feature ceased to decrease and began to increase and negative disparity was proportionally applied. The air mode three dimensional model employed positive disparity for those objects appearing within the displayed range (120 NM). The sensor segment representing ownship radar coverage was modeled with continuous positive disparity and appeared to recede into the display. However, unlike ground mode, the features of the sensor segment remained fixed relative to ownship. Maximum parallax was 5.8 mm or 28 minutes of uncrossed disparity at the 711 mm viewing distance.

4.2.3 Horizontal Situation Format

The Horizontal Situation Format (HSF) was a plan view display that showed ownship, the planned flight route, terrain data, and threat information.

4.2.3.1 Horizontal Situation Format Description

An example of the Horizontal Situation Format, ground mode is shown in Figure 4.2-6. Ownship was represented by a cyan

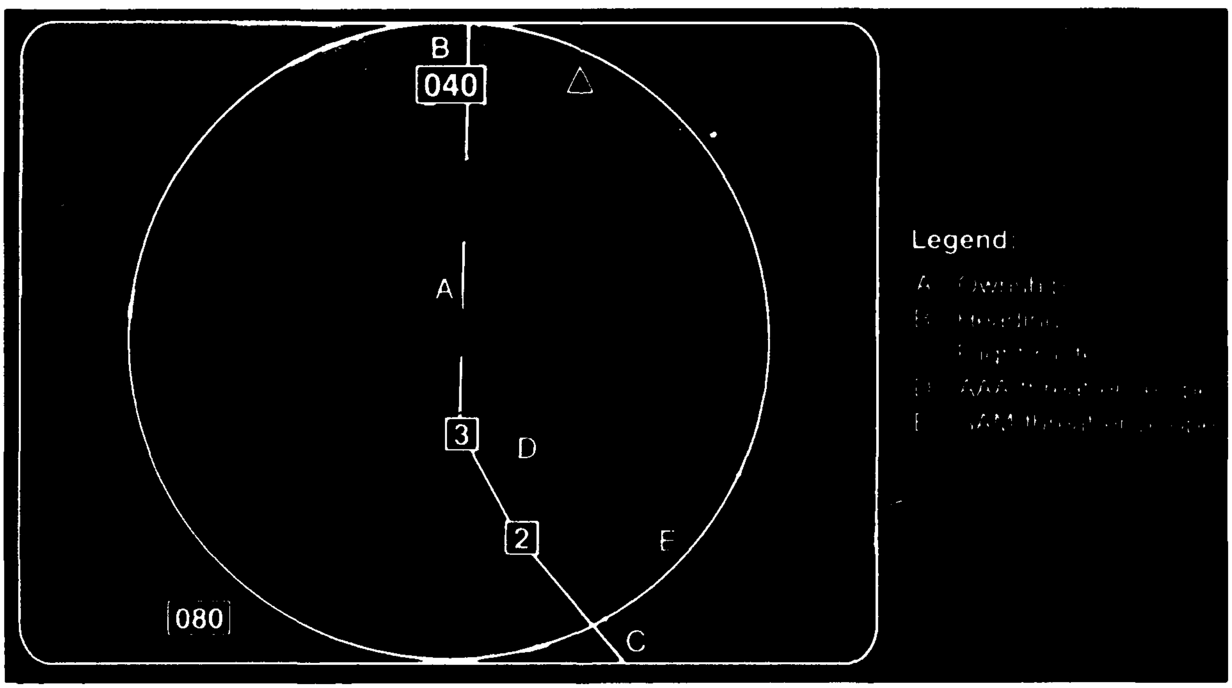


Figure 4.2-6. Horizontal Situation Format, Ground Mode

aircraft symbol (A) in the center of the display enclosed by the outer range ring. The scale readout in the lower left corner of the display indicated range from ownship to the outer range ring. The format was always oriented ownship heading up. The heading readout was a white three digit number, centered along the top edge of the format (B). The planned course (C), appeared as a series of white line segments from waypoint to waypoint. Waypoints occurred at changes of heading and were designated by numbered squares along the route. Terrain above current ownship altitude was shown in brown. The forward line of troops (FLOT) was represented as a series of solid amber triangles, pointing toward enemy territory; the triangles were attached to an amber line.

The HSF in ground mode showed surface threat type, location, mode, and lethality area. For surface-to-air threats, threat envelopes were depicted as cross sections (at current ownship altitude) of the three-dimensional threat volumes shown on the PSF. An individual AAA was shown as a red octagon and represented an area of uniform high lethality (D). A SAM (E) was shown as a pair of concentric irregular hexagons. The inner red hexagon represented an area of high lethality; the outer amber hexagon, an area of reduced lethality.

On the HSF, four threat modes were depicted: prebriefed, search, track, and launch. Lethality areas for prebriefed threats were shown in the outline form only. Active threats were shown in the solid form. In track mode, an amber tractor beam connected the threat to ownship and an amber lock-on ring enclosed ownship. For threats in launch/fire mode, the tractor beam and lock-on ring were coded red. For inbound missiles, a missile symbol was added to the tractor beam which showed the current position of the missile. The missile symbol was a small, solid red circle, outlined in black, with a black "I" (infrared) or "R" (radar), indicating missile type. The missile symbol absorbed the tractor beam as it travels toward ownship. If lock was broken in track or launch/fire mode, the tractor beam and lock-on ring vanished. With a launched missile, the missile continued to fly along the same course once lock was broken until considered dead, then it too vanished.

During each mission, a ground target symbol was added to the HSF. The target appeared as a small white outline triangle. Following pilot cursor designation of the target, the symbol was changed to amber outline and the delivery point symbol was added to the display. The amber color coding of the target indicated that the weapon had been successfully designated but was not yet in range. The delivery point symbol appeared as a small white outline square. Once ownship reached the closest point of approach to the target, the target symbol was changed to green outline.

Symbology unique to the air mode HSF is illustrated in Figure 4.2-7. Ownship (A) is shown in the offset position. The unique symbology included: aircraft symbols, sensor information, MLEs, and weapon status halos. Other aircraft were shown as red

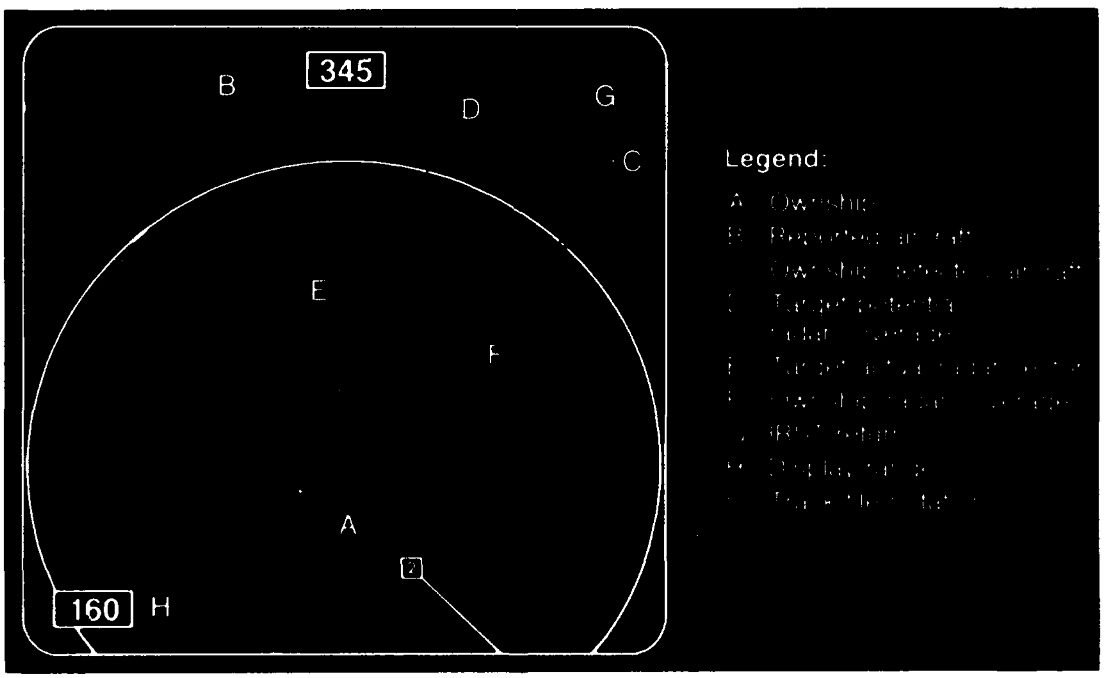


Figure 4.2-7. Horizontal Situation Format, Air Mode

triangles for enemies, amber squares for unknowns, and green circles for friendlies.

Reported aircraft (those not detected by ownship's sensors) were shown in the outline form (B). Aircraft detected by ownship's sensors were shown in the solid form (C). Each aircraft detected by ownship sensors had a vector pointing in the direction of flight. If a detected aircraft's radar was not on, its potential radar coverage was shown as a 90° sector, with a dotted amber line (D). In search mode, the area of coverage was shown as solid amber outline (E). Ownship's potential radar coverage was shown as a 90° sector, with a dotted cyan line. When ownship's radar was on, actual radar coverage was shown as solid cyan outline (F). An IRST return was shown as a dashed line extending to the edge of the display (G) and bounding the detected target.

Detected aircraft could be selected for Close Look display with the use of a specified cursor function. After selection, the aircraft were enclosed in a set of four cyan box corners (I), the Close Look display indication, indicating that the aircraft were available for Close Look display. As subsequent selections were executed, those previous were enclosed by a pair of white box corners, the track file indication, identified by letter and accessible via indicated side switches. The letter designation above the box corners was the track file name.

The HSF MLE symbology (Figure 4.2-8) for both ownship and the target or threat aircraft were displayed simultaneously either when ownship designated a target or when a threat aircraft tracked ownship. The ownship MLE (MLE-O) was composed of two elongated, color coded "L" sections placed end to end. The origin of the first section of the MLE-O occurred at Rmin for ownship's selected missile against the designated target. The first section (from Rmin to Rmax2) was coded white and displayed the approximate no-escape zone for onboard radar missiles against the current designated target. The second "L" section

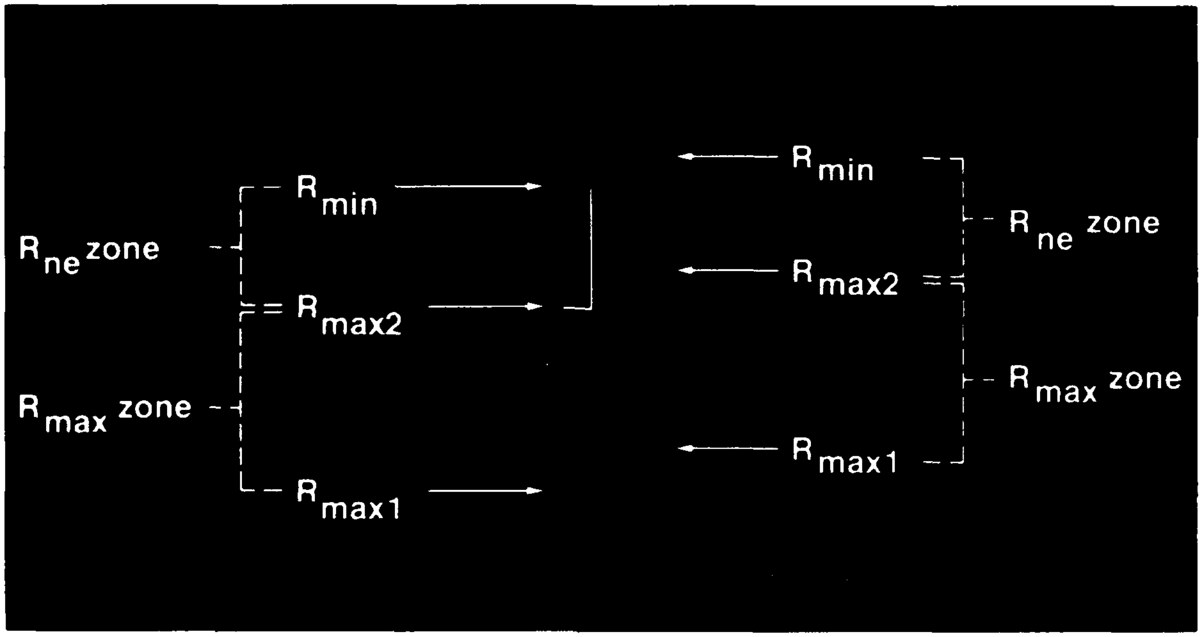


Figure 4.2-8. HSF Missile Launch Envelopes

of the MLE-O was attached to the white no-escape section at the Rmax2 point. This second section (from Rmax2 to Rmax1) was coded green and displayed the *approximate* maximum range for onboard radar missiles against the current designated target.

The threat MLE (MLE-T) was similar to MLE-O, composed of a pair of elongated, color coded "L" sections, placed end to end. The origin of the first "L" section of the MLE-T represented Rmin for the expected radar missile of the threat against ownship. The MLE-T and its origin were ownship referenced (as is the MLE-O), consequently, the origin was positioned in close proximity to the threat. The first section of the MLE-T (from Rmin to Rmax2) was coded red and displayed the approximate no-escape zone for threat missiles against ownship. The second "L" section of the MLE-T was attached to the red no-escape section at the Rmax2 point. This second section was coded amber and displayed the approximate maximum range for threat missiles against ownship. The MLE pairs were displayed, side by side from their respective points of origin, positioned in close proximity to the threat. The MLE-O and MLE-T always pointed toward ownship, regardless of the aspect of the threat aircraft.

The amber and red lock-on rings were used to indicate a threat track or launch, respectively, upon ownship.

If ownship launched upon a threat aircraft that was not actively tracking ownship, the MLE symbology was replaced by a cyan tractor beam and missile symbol to indicate weapon position in flight. However, for tracking threat aircraft, the MLE-T symbology was retained. A threat aircraft which launched upon ownship was considered to be in track mode, i.e., launch was a special case of track. Thus, in addition to the continued display of MLE symbology and the red lock on ring, a red tractor beam and missile symbol were added to the HSF.

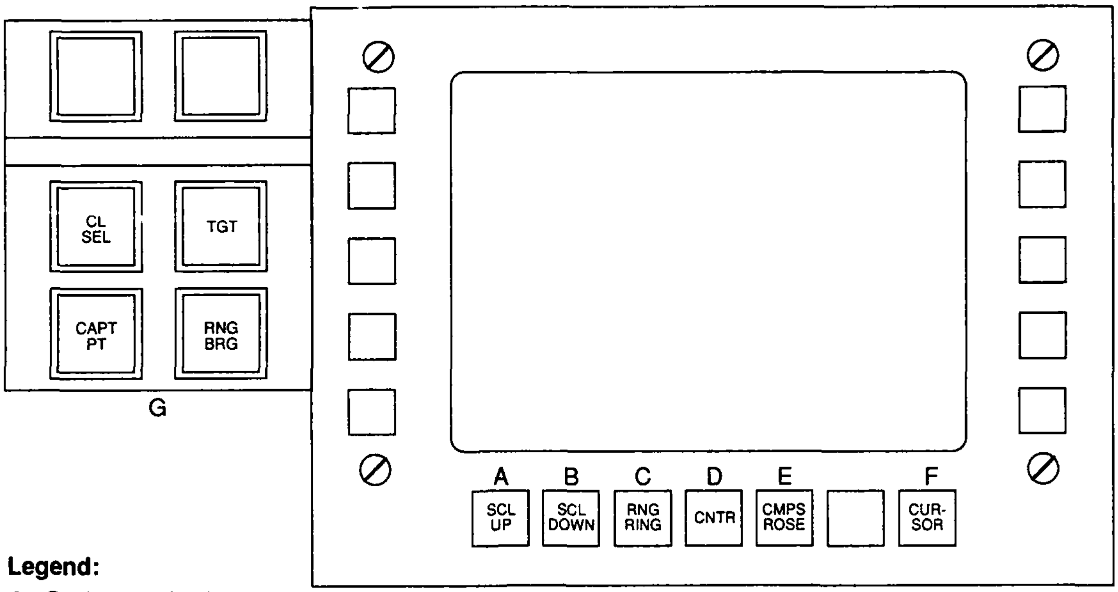
Pilot target designations in air mode were executed on the CLF. On the HSF, weapon status was shown by the color coding of an enclosing disc, added to an aircraft symbol. The disc was coded amber when a weapon was targeted, green when weapon launch criteria (range and master arm) were met, and white with weapon launch.

4.2.3.2 Horizontal Situation Format Options

Controls associated with the Horizontal Situation Format are shown in Figure 4.2-9. In the row of switches below the display, scale up and scale down selection (A and B) increased or decreased the displayed range. RNG RING added or deleted three intermediate range rings (C) from the format. The ownship center/offset selection (D) shifted the ownship position within the display such that ownship was offset one quarter from the lower edge of the display. CMPS ROSE (E) added or deleted a compass rose to the outer range ring. The CURSOR switch (F) and the Cursor Definition Panel (G) were used to access and define a specific function for the cursor.

4.2.3.3 3-D Features of the Horizontal Situation Format

Disparity was used in the HSF to model altitude differences



Legend:

A Scale up selections
B Scale down selections
C Range rings
D Ownship center/offset selection
E C.mpass rose
F Cursor access
G Cursor definition panel

Figure 4.2-9. Horizontal Situation Format Option Switches

relative to ownship. Ownship was fixed at the display plane as were co-altitude ground threat and terrain cross sections. The planned flight route, specified at a given altitude, could appear above or below the display plane as a function of ownship altitude. Display features below ownship appeared to recede into the display and those above appeared to protrude. The disparity of each symbol was proportional to the altitude difference. The HSF in ground mode modeled altitudes from zero to 5000 feet. 3-D air mode features were modeled from zero to 50,000 feet. Maximum parallax was 9.0 mm or 40.5 minutes of disparity at the 762 mm viewing distance.

4.2.4 Navigation

Figure 4.2-10 shows four different navigation conditions as they appeared on the HUD. With coupled navigation, the display provided guidance to some reference. Normally, the reference was the preplanned flight route. In this mode, the HUD appeared with a white pathway and commands on the speed, heading and altitude parameters as in the upper left of Figure 4.2-10. In this mode, if the pathway was flown outside the HUD field of view, the coupled cyan pitch ladder appeared as in the upper right of the figure with the command arrows on airspeed, reading and altitude readouts still providing guidance.

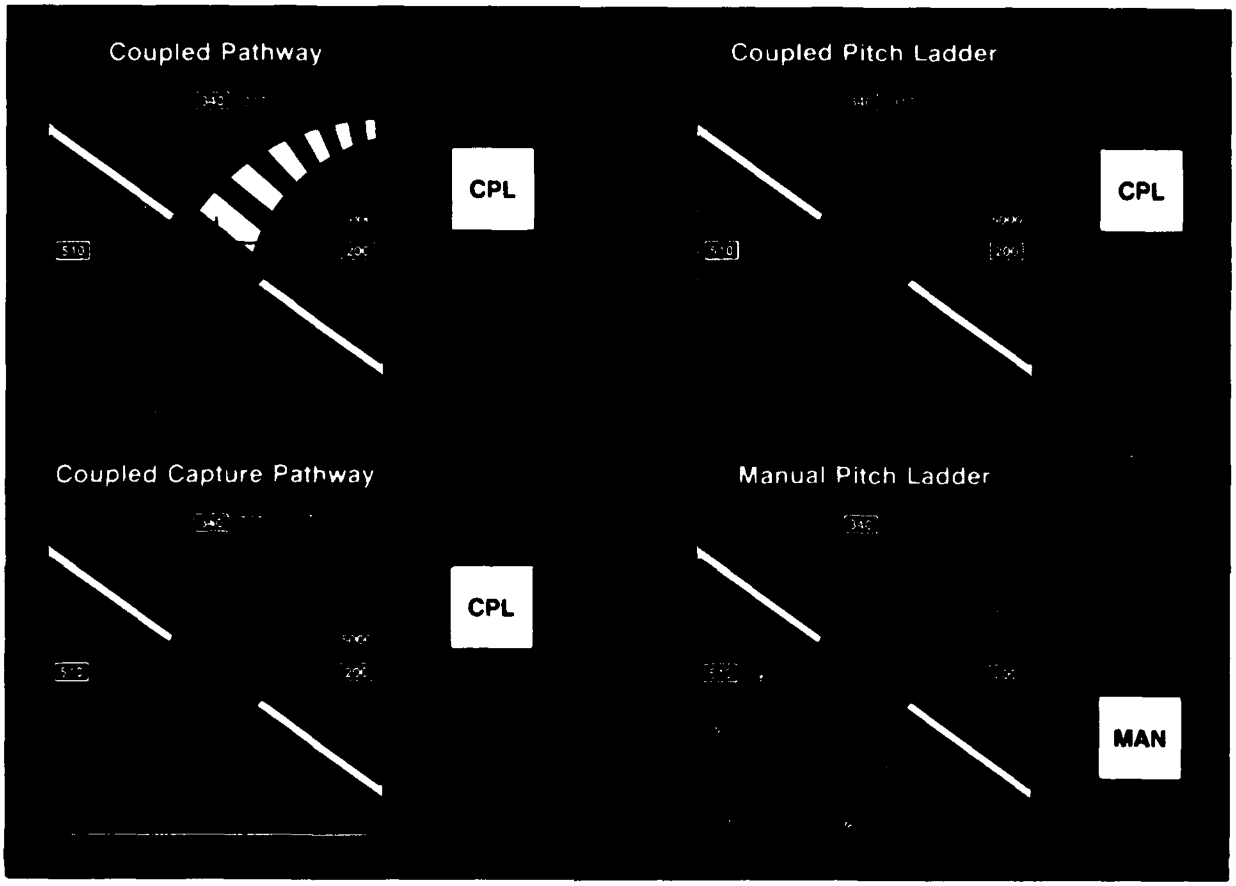


Figure 4.2-10. HUD Display of Navigation Modes

The third form, coupled capture pathway, was available with execution of a cursor function. The capture pathway cursor function was used to select a waypoint to intercept the nominal flight path. Following selection of the capture waypoint, the navigation system generated a cyan pathway from ownship position to the selected capture waypoint and provided commanded values for the flight parameters as shown in the lower left. The capture pathway generated and displayed on the HUD, PSF, and HSF was identical to the nominal flight path with the single exception of the cyan coding.

Alternatively the pilot could select the manual mode. In this case, the HUD presented a white pitch ladder without commanded values, as shown in the lower right of Figure 4.2-10.

4.2.5 Close-Look Formats

The Close-Look Formats (CLF) provided detailed information on the identity, status, location, velocity vector and configuration of airborne traffic. The aircraft to be displayed on the CLF were selected from the HSF; the Close-Look Format then replaced the Perspective Situation Format on the center MPD. There were two CLFs available: Plan View and Vertical View, described below. The pilot could select between them with a switch under the center MPD.

Several display elements were common to both CLF views. The common display symbology included the composite symbols representing individual aircraft, the identification (ID) number associated with an aircraft, the ID side switches, the three optional data lines associated with the ID side switches, and ownship heading. The centroid of the formation, the weapons targeted note, and the display scale readout appeared and functioned identically in each view.

The composite symbols representing individual aircraft in the formation had a number of individual features. The innermost element, the aircraft symbol, was a red triangle, amber square, or green circle for adversary, unknown, or friendly aircraft, respectively. This follows common Joint Tactical Information Distribution System (JTIDS) symbology. In addition to the aircraft symbol, the composite symbol could include the target sequence ring and weapon status area (Figure 4.2-11), as required. A white or cyan target sequence ring was added to the aircraft symbol as a function of target designation. The first target designated by the pilot was the primary target and was

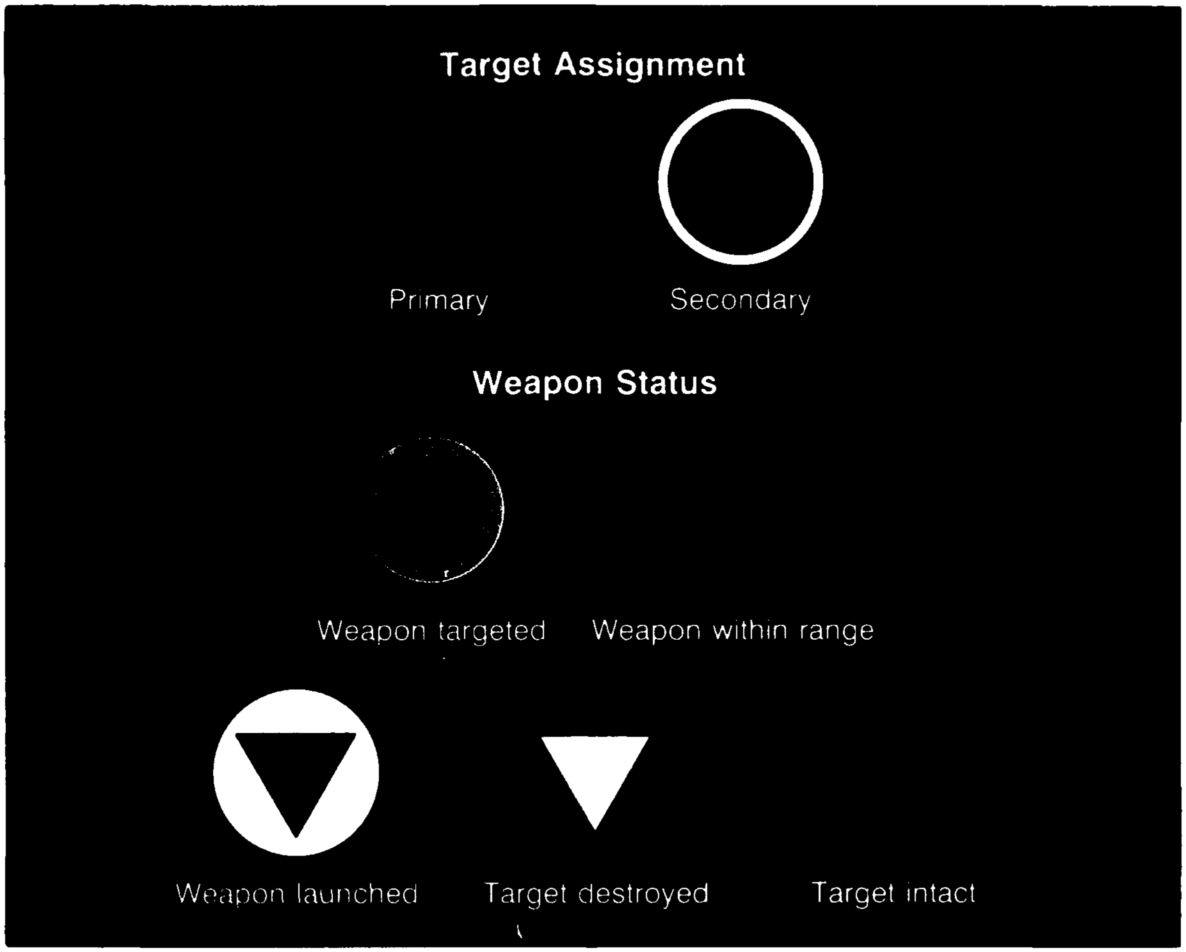


Figure 4.2-11. CL^E Composite Aircraft Symbology

enclosed with a cyan target sequence ring. Subsequent target designations were enclosed with white target sequence rings. Once the primary target was fired upon, the cyan target sequence ring was replaced with the white weapon launch coding. Then the next target in the designated sequence gained the cyan sequence ring. Target sequence was determined by the order in which the pilot made designations.

Weapon status was shown by area color between the sequence ring and the aircraft symbol. The area was amber when a weapon was targeted, green when weapon launch criteria (range and master arm) were met, and white upon weapon launch. With missile impact and destruction of the target, the triangle was coded white with red outline for 10 seconds, then vanished. A miss was indicated by leaving the target symbol in its original shape and color.

Each aircraft symbol included a single digit black ID number which corresponded to an ID side switch. The side pushbutton switches, located along the left and right edges of the center MPD, were used to target weapons to the displayed aircraft. The ID side switches were labeled by single white digits on the black display background. Associated with each ID side switch were three optional data lines, discussed in Section 4.2.5.3, Close-Look Format Options.

Ownship heading was displayed in a readout at the top center of the display. A small white letter in the center of the CLF indicated the centroid of the formation. The centroid remained at the geometric center of the display surface. The centroid was also the reference position for the Plan View range readout and ownship bearing vector or the ownship altitude vector of the Vertical View. The letter identified the current formation selected for Close-Look display, corresponding to the formation enclosed with the CL Display Indicator in the HSF.

With the targeting of AIMs, accomplished using the side switches of the center MPD, a note was added to the display which identified the number and type of weapons to be fired with actuation of the trigger. This was the same note that appeared on the HUD. Display range scale, in nautical miles, was shown in a white readout in the lower left corner of the format. Range for the CLF was defined as height of the display in nautical miles. Available display range scales were 5, 10, 15, and 20 nautical miles.

4.2.5.1 Plan View Close-Look Format

The Plan View Close-Look Format showed a range by range section of airspace selected from the Horizontal Situation Format (HSF). The Plan View was oriented ownship heading up, like the HSF.

Unique to the Plan View CLF (Figure 4.2-12) was the aircraft velocity vector (B), the ownship bearing vector (C), the altitude data line (D), and the ownship range readout (E). Velocity vectors were attached to the composite symbols. The aircraft symbol and velocity vector rotated to show aircraft heading. The ownship bearing vector pointed back to ownship position; the readout for range between Plan View centroid and ownship appeared in the lower right corner of the CLF, in the form XXX NM. The third data line showed individual aircraft altitude in the form XX K. "Data," a CLF option is discussed in Section 4.2.5.3.

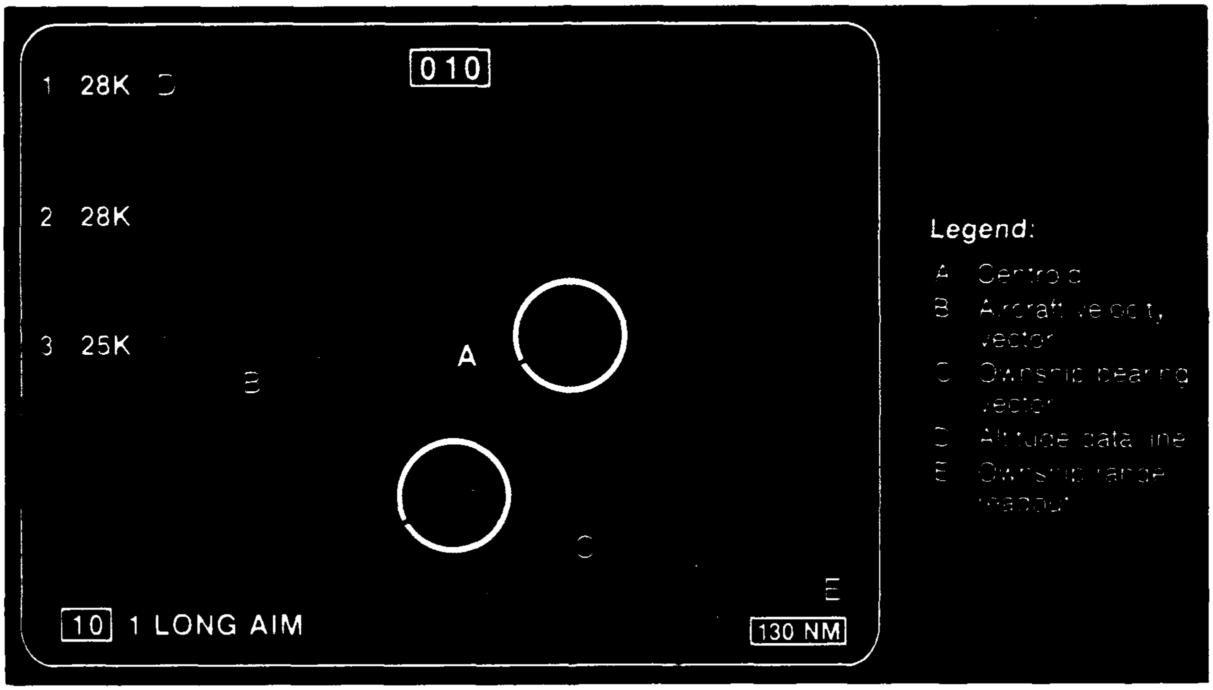


Figure 4.2-12. Close-Look Format, Plan View

4.2.5.2 Vertical View Close-Look Format

The Vertical View Close-Look Format (Figure 4.2-13) displayed a range by altitude section of airspace selected from the HSF. The range (width) and altitude (height) of the Vertical View corresponded to the display scale readout, in nautical miles. Unique to the Vertical View CLF was the centroid altitude readout (B), the ownship altitude vector (C), and the heading

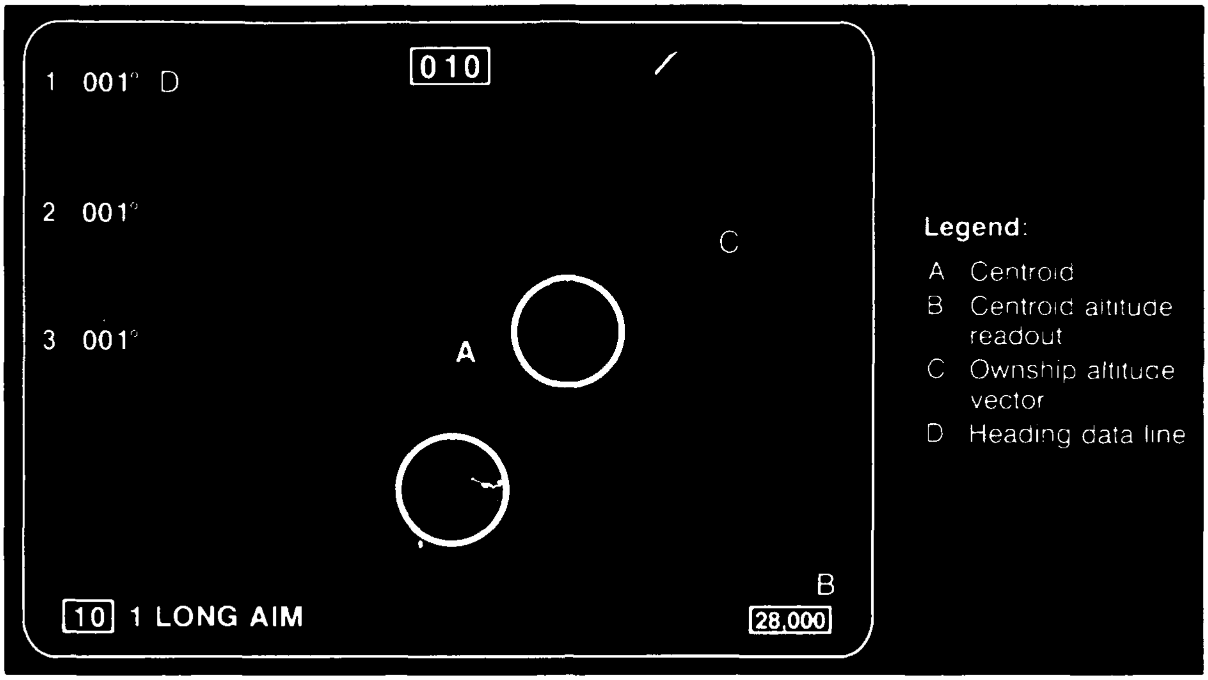
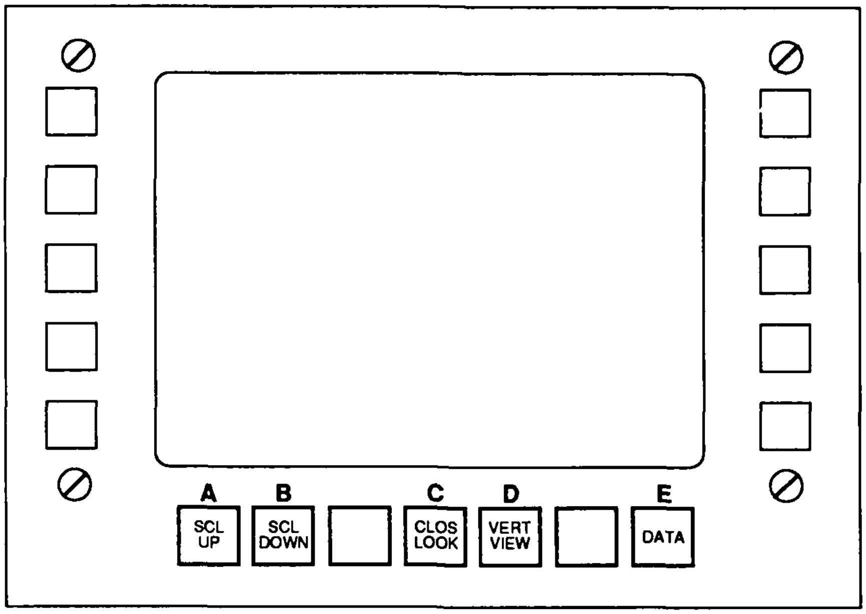


Figure 4.2-13. Close-Look Format, Vertical View

data line (D). The centroid altitude readout appeared in the lower right corner of the format in the form XXXXX. The ownship altitude vector, positioned along the display edge, pointed back to ownship altitude. The vector provided an indication of ownship position and altitude relative to the Vertical View's displayed formation. The third data line showed aircraft heading in the form XXX°.

4.2.5.3 Close-Look Format Options

The Close-Look Format option switches are shown in Figure 4.2-14. The top four of the column of switches on each side of the display were used to target air-to-air missiles to the FIG/ aircraft whose ID numbers appeared next to the ID side switches. SCALE UP and SCALE DOWN selections (A and B) increased and decreased the displayed range. The CLOSE-LOOK switch (C) was used to select the Close-Look Formats for display or return the Perspective Situation Format to the center MPD. The VERT VIEW switch (D) was used to toggle between the CLF Plan View and the CLF Vertical View. DATA was used to access, cycle through the



Legend:
A Scale up selections
B Scale down selections
C CLF display access
D CLF vertical view
E Data line selection

Figure 4.2-14. Close-Look Format Option Switches

three data lines, and return to the available state. For the CLF Plan View, four successive selections of the DATA Switch cycled among 1) aircraft type, 2) airspeed, 3) altitude, and 4) the absence of a data line. Similarly, for the Vertical View, four successive selections resulted in 1) aircraft type, 2) airspeed, 3) heading, and 4) the absence of a data line.

4.2.5.4 3-D Features of the Close-Look Formats

In the 3-D condition, the airplane symbols in the Plan and Vertical View had disparity added. All other symbology appeared in the display plane. In the Plan View, the composite symbol representing an individual aircraft - the aircraft symbol, ID number, target sequence ring, weapon status area, and vector - was at a single plane. The aircraft were separated in disparity by amounts proportional to their distance from the altitude centroid of the formation. The composite symbols for aircraft above the centroid were shown with negative disparity and those for aircraft below the centroid had positive disparity. In the Vertical View, symbols for individual aircraft had disparity added proportional to their distance from the range centroid of the formation. Maximum parallax was 7.4 mm or 40.6 minutes of disparity at 711 mm viewing distance. This limit was reached at 5000 feet altitude difference in the plan view and 5 NM range difference in the vertical view.

4.2.6 Cursor Functions

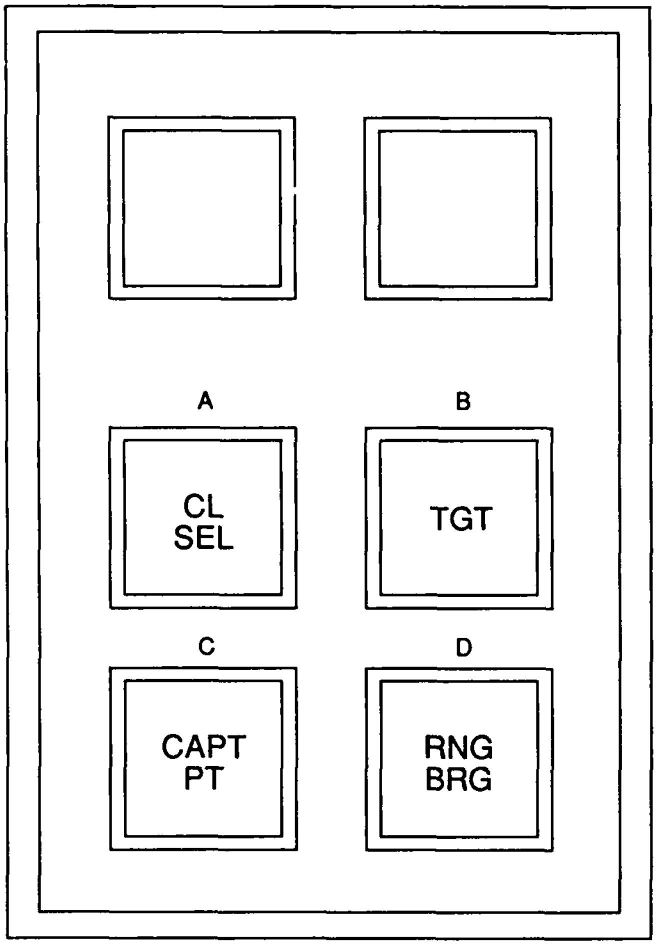
A number of cursor functions were required in this simulation. The following sections provide information on how specific cursor functions operated on the HSF.

When the pilot pressed the CURSOR switch located under the lower MPD the general cursor symbol appeared over the ownship symbol on the HSF. The pilot then used the isometric cursor control on the flight control stick to place the general cursor on the desired location on the HSF. With the location of interest thus marked, the pilot selected a specific cursor function from the Cursor Definition Panel. If the location of the general cursor symbol was determined to be invalid for the selected cursor function, the cursor flashed for three seconds and vanished; the cursor access procedure had to begin again.

The switches of the Cursor Definition Panel (Figure 4.2-15) were used to access the Close-Look Format, to select a capture pathway waypoint, to target air-to-ground weapons, or to select a location for a momentary range/bearing readout. Following the selection of a specific cursor function, the general cursor symbol was replaced with one of the special function cursor symbols (Figure 4.2-16) as described in the subsequent sections.

4.2.6.1 Close-Look Format Selection

The cursor was used, in air mode, to select a portion of the HSF



Legend:

A Close-look format selection
B Target selection
C Capture pathway waypoint selection
D Range/bearing readout

Figure 4.2-15. Cursor Definition Panel

Symbol	Appearance
General	○
CL display indication	⌜ ⌝ ⌞ ⌟
Capture pathway waypoint	□
Target	△
Range/bearing location	+

Figure 4.2-16. HSF Cursor Symbols

for closer examination. The Close-Look Formats were displayed on the center MPD and provided detailed information about an aircraft or a formation of aircraft.

To access the Close-Look Format the pilot pressed the CURSOR switch. Then he used the CURSOR CONTROL moving the general cursor to the desired aircraft or formation on the HSF. Finally the pilot selected the CL SEL switch on the cursor definition panel and pressed the CLOSE-LOOK switch under the center MPD.

Once the CLOSE-LOOK switch had been selected, the CLF Plan View was displayed on the center MPD. A pilot could also use the CLOSE-LOOK switch to toggle between the Close-Look Format and the Perspective Situation Format, air mode.

4.2.6.2 Target Selection

In ground mode, the pilot used the HSF cursor in conjunction with the target switch to select a target for the antiradiation missile, or the bombs. The designated positions of bomb targets were displayed symbolically in the HSF (an open triangle) as the target was updated in flight. Following target selection, SAM or AAA sites targeted fo: the antiradiation missiles also included the appropriately coded target symbol.

To target antiradiation missiles or bombs the pilot selected the appropriate weapon, selected the CURSOR switch and used the CURSOR CONTROL to place the cursor (on the HSF) on the selected SAM or AAA site or the designated target position. The pilot then selected the target switch (TGT) to insert the location.

Weapon assignment was accomplished with the selection of the target switch. Designated ground target symbols were coded amber if weapon assignment is accepted. When a SAM or AAA site had been targeted with an antiradiation missile, the appropriately coded target symbol was added to the site on the HSF. The air-to-ground target/weapon assignment remained as inserted until the weapon was released, actively deselected, the target was overflown or the air mode was selected.

4.2.6.3 Capture Pathway Waypoint Selection

The capture pathway procedure required the pilot to select a waypoint from the nominal flight path, effectively defining an intercept point. Following selection of the waypoint, the capture pathway of the HUD, coded cyan, was generated from ownship's current position to the waypoint.

To execute the capture waypoint selection procedure, the pilot selected the CURSOR switch from below the HSF and used the CURSOR CONTROL to mark the desired intercept waypoint. The pilot then selected the CAPT PT switch from the Cursor Definition Panel.

With selection of the CAPT PT switch, the cyan capture pathway was added to the HUD and the PSF. In the HSF, new course was displayed as a cyan line extending from the ownship symbol to the selected waypoint. The capture waypoint was coded cyan in each display.

4.2.6.4 Range/Bearing Readout

The pilot used the cursor to designate a location on the HSF for determination of range and bearing. A location was identified with the cursor and the RNG BRG switch of the Cursor Definition Panel was selected. This would display in the lower right corner of the HSF range and bearing from ownship to the selected location.

4.3 Sensor System

This aircraft was assumed to be equipped with an advanced multimode sensor system. The intent in both air and ground modes was to acquire the necessary information but to minimize radiation from ownship. In air mode, IRST was used for initial detection and early tracking, radar was used only when precision was required. Sensor systems operated automatically with the returns processed and presented on the HUD and the situation formats as previously discussed. There was assumed to be a passive sensor system which provided information about the battle environment in a sphere around the aircraft. Figure 4.3-1 is the Sensor Coverage Status Format which represented the condition of the passive sensor system. If all the sensors in the system were functioning correctly, the wire frame around ownship was coded white.

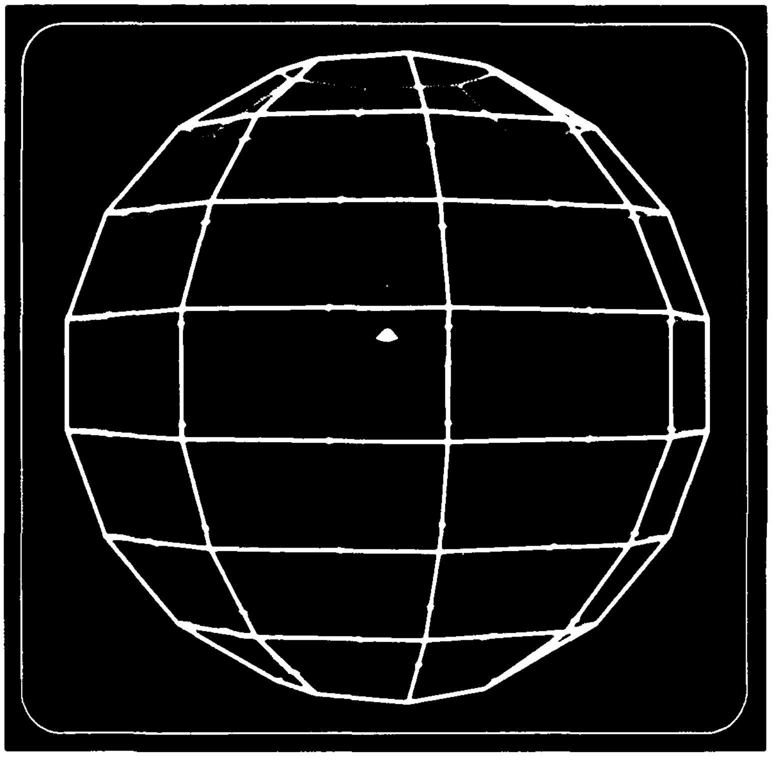


Figure 4.3-1. Sensor Coverage Status Format

4.4 Stores System

The stores system of the aircraft included the stores controls, the stores and countermeasures status format, and the stores themselves. These subsystems are described in the following paragraphs.

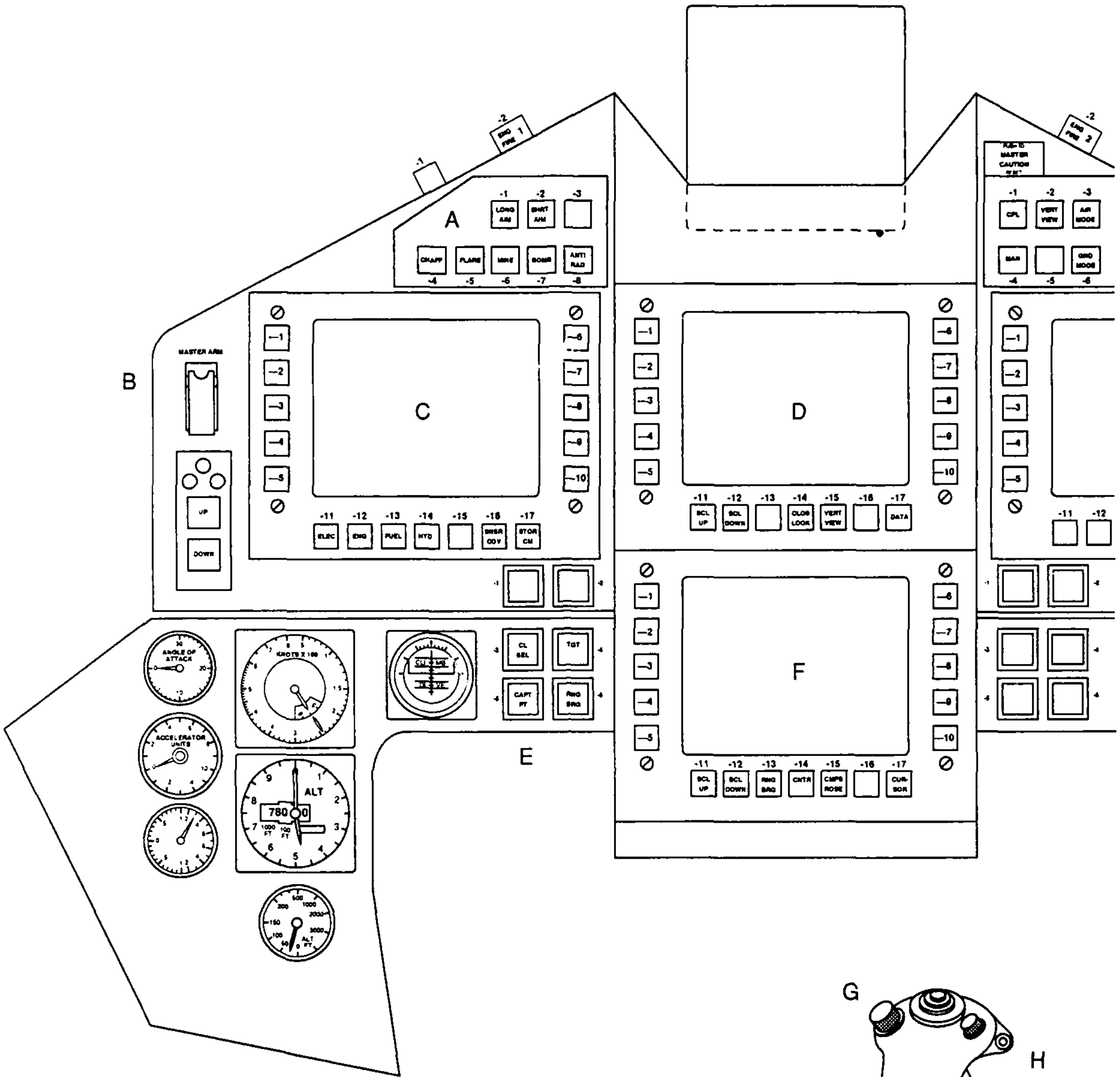
4.4.1 Stores System Controls

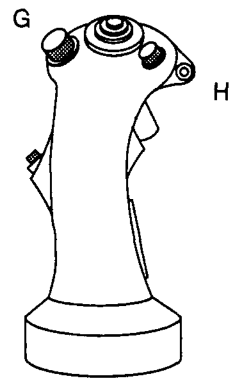
Figure 4.4-1 shows the controls for the stores system. The master arm switch (B) had to be turned on for the stores to release. Specific stores were selected for delivery from the stores and countermeasures panel (A) above the left MPD. AIM's were targeted using the Close-Look Format on the center MPD (D). Ground targets were designated using the cursor on the Horizontal Situation Format (F), the cursor control on the stick (G), and the target switch on the cursor definition panel to the left of the lower MPD (E).

4.4.2 Stores and Countermeasures Status Format: Weapons

The combined stores and countermeasures status format used in the aircraft is depicted in Figure 4.4-2. The format was displayed on the left MPD. The weapons part of the format is discussed here. Symbols representing individual stores were arrayed forward and along the leading edge of the aircraft plan view outline in the format. In air mode, two short AIMs were shown near the wingtips, four long AIMs were shown near the centerline. In ground mode, two anti-radiation missiles, two guided mine canisters and two guided bombs were shown on the wing stations. In both modes the gun was shown in the nose.

To fire a weapon, the master arm switch had to be turned on, the weapon had to be selected and targeted, and the target had to be in range. Table 4.4-1 illustrates the combinations of these conditions and the appearance of the symbol(s) for the particular stores(s). Note that the appearance of the weapon body (outline, amber, and green) reflected onboard system state (store selected, and master arm). The appearance of the halo (absent, outline, amber, or green) reflected the state of readiness of that particular store (targeted and in range). When all release parameters for a particular weapon were met, both the weapon body and the halo were green.





Legend:

Stores controls

A Stores select panel
B Master arm switch
C Left MPD—stores and countermeasures format
D Center MPD—close look format
E Cursor definition panel
F Lower MPD—horizontal situation format

Onflight control stick

G Cursor control
H Trigger

Figure 4.4-1. Stores System Controls and Displays

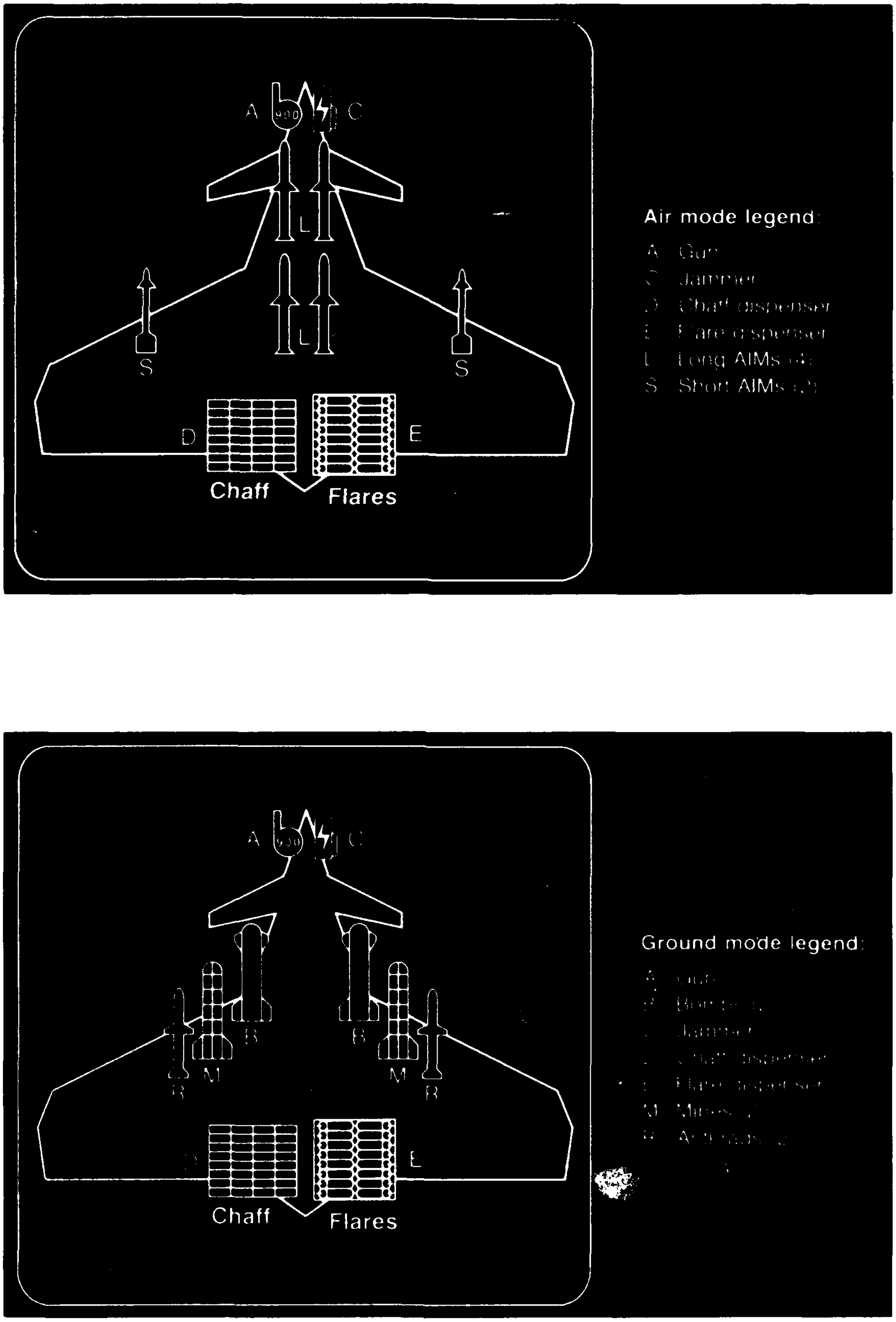


Figure 4.4-2. Stores and Countermeasures Status Format

Table 4.4-1. Stores Status Coding

Symbol appearance		Status			
Weapon	Halo	Selected	Master arm	Targeted	In range
White outline	Absent	No	N/A	N/A	N/A
White outline	Amber fill	No	N/A	Yes	No
White outline	Green fill	No	N/A	Yes	Yes
Amber fill	White outline	Yes	Off	No	N/A
Amber fill	Amber fill	Yes	Off	Yes	No
Amber fill	Green fill	Yes	Off	Yes	Yes
Green fill	White outline	Yes	On	No	N/A
Green fill	Amber fill	Yes	On	Yes	No
Green fill	Green fill	Yes	On	Yes	Yes
Absent	Absent	Not on board			

4.4.3 Delivery Procedures, Air Missions

Since the air missions in this program were all beyond-visual-range (BVR), the guns and SHORT AIMs were not used. Pilots were instructed that early in an air-to-air engagement they should check that the Master Arm switch was on, select LONG AIM on the panel above the left MPD, and call up the Store and Countermeasures Status Format for display on the left MPD.

Later, when raid count and IFFN information had developed, the pilot could assign long AIMs to targets, using the Close Look Format. In the Close Look Format, aircraft ID numbers for targetable aircraft were arranged next to the ID side switches on the center MPD. Targetable aircraft were those which had been identified as adversaries, had been selected for presentation on the Close Look Format, and were within the sensor field of view. ID side switches next to aircraft ID numbers for non-targetable aircraft were unavailable.

To assign long AIM's to targets, pilots selected the switch(es) next to the appropriate identification number(s). Missiles could be assigned up to the quantity remaining on board. For simple deselection, they pressed the selection button a second time. They then checked for missile ready indications (weapon body and halo green) on the Stores and Countermeasures Status

Format. Finally, they used the HUD, the Close Look Format, and the Horizontal Situation Format, to determine the appropriate time to fire. If launch conditions were met, a trigger pull would launch the selected AIM at the first designated target.

4.4.4 Delivery Procedures, Ground Missions

For the air-to-ground missions the aircraft carries a gun, two antiradiation missiles, two guided bombs, and two guided mine canisters. All but the gun and the mines were available for use.

4.4.4.1 Antiradiation Missiles

Two antiradiation missiles were carried for self-protection. The missiles used the aircraft system for detection of threats, the pilot for targeting and their own broad-band seekers for in-flight guidance. Since only two antiradiation missiles were carried, pilots were cautioned to reserve them for unavoidable threats in active or track mode.

To prepare for launch of an antiradiation missile the pilot turned on the Master Arm switch, selected ANTIRAD on the panel over the left MPD, called up the Stores and Countermeasures Status Format for display on the left MPD and designated the target using the target cursor option.

To fire an antiradiation missile, the pilot called up the Stores and Countermeasures Status Format on the left MPD, checked for missile ready indication on that format and pulled the trigger when he saw the word SHOOT on the HUD.

4.4.4.2 Bombs

The aircraft carried two powered, homing, launch and leave, glide bombs. They could be delivered from low altitude. Their guidance, control, and propulsion features allowed them to be deployed against a variety of targets in a relatively large area around the launch point. The bombs had an automatic guidance mode in which they accepted and attacked targets at coordinates established with the target cursor option. Bomb selection and target designation occurred inflight.

To prepare for bomb delivery the pilot turned on the Master Arm switch, selected BOMB on the panel above the left MPD, called up the Stores and Countermeasures Status Format for display on the left MPD, and designated the assigned target using the target cursor option.

To deliver the bombs, the pilot called up the Stores and Countermeasures Status Format on the left MPD, checked there for bomb ready indication, and pulled the trigger when he saw SHOOT on the HUD.

4.5 Countermeasures System

The countermeasures system in this aircraft consisted of an electronic RF jammer, a chaff dispenser, and a flare dispenser. The Stores and Countermeasures Status Format (Figure 4.4-2) displayed status of the countermeasures system.

4.5.1 Jammer

The jammer operated automatically without pilot intervention, responding to threats which were tracking ownship. The jammer symbol in the nose of the combined format showed the status of the jammer. When it was off, the symbol was drawn in white outline with a white lighting bolt inside. When it was in standby, the symbol was solid amber with a black lighting bolt inside. When the jammer was on, it was shown solid green with two amber lightning bolts outside.

4.5.2 Chaff and Flares

Full loads were represented as eight rows of four chaff bundles each and eight rows of two flares each. When the avionic system detected a launch upon ownship, launched missile type information was displayed in the HSF and the HUD. A requirement for expenditure of chaff or flares was indicated with amber coding of a single row. The pilot was to select the chaff or flare switch as appropriate. Once the pilot selected either chaff or flares, the row to be dispensed was coded green. At the proper time, the system released the selected countermeasures. Following countermeasures release, the expended row vanished from the dispenser shown on the format.

4.6 Propulsion System

The aircraft had two engines, equipped with fully modulated afterburners and three dimensional nozzles. The two thrust levers were located on the top of the thrust quadrant, just outboard of the pilot's left leg. The levers moved from flight idle, through a detent at military power, through the afterburner range to maximum thrust.

Figure 4.6-1 shows the elements of the engine status format, available on the left MPD. It showed actual thrust, required thrust, throttle position, fuel flow and an engine flame for each engine. Exhaust gas temperature and oil pressure and quantity were displayed only in the event of a malfunction or failure.

Required thrust was calculated as a function of airspeed based upon the nominal flight route. It was indicated by a pair of cyan triangular pointers (A) which moved vertically along the engine body shapes. Current throttle position (B) was shown by the outer 20 percent of the vertical thrust bar inside the engine body. Actual thrust (C) was the remainder of the thrust bar and represented an integrated measure of thrust that

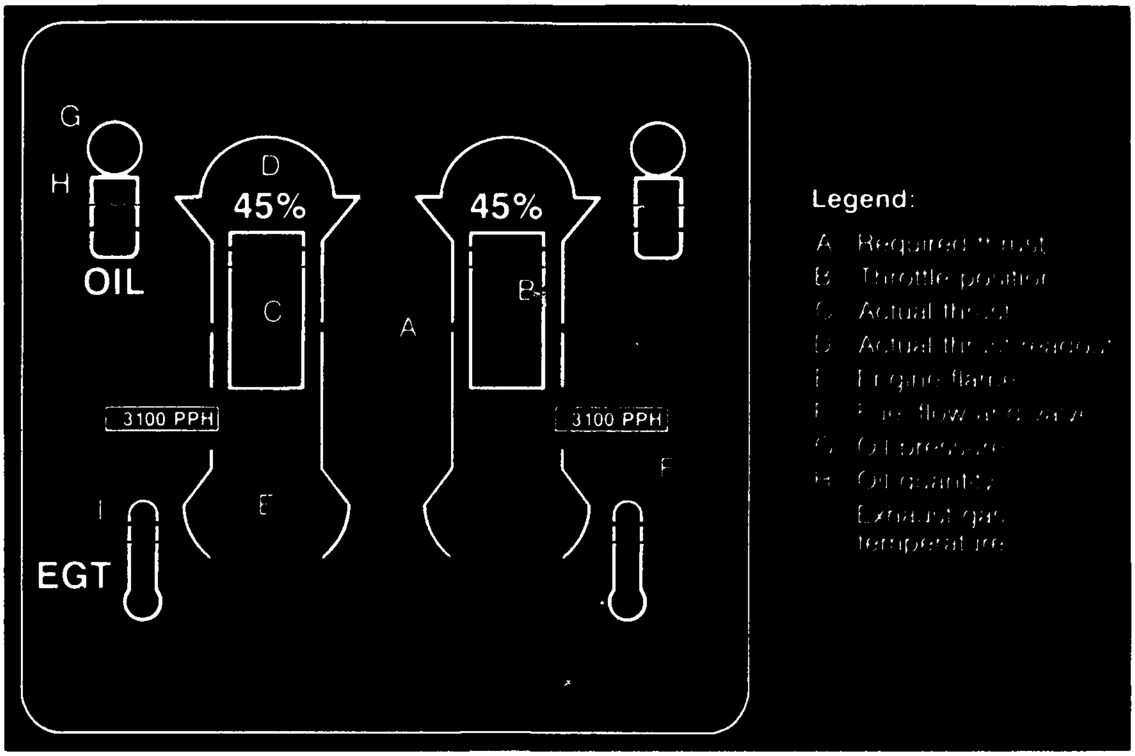


Figure 4.6-1. Elements of the Engine Status Format

incorporated relevant engine and environmental parameters. Throttle position and composite thrust were represented by solid cyan fill. The actual thrust readout registered from 0 to 100%. Flight idle occurred at 5% and the military (dry) setting at approximately 50% - the detent throttle position. Afterburner operated at thrust levels above 50% as indicated by the amber line within the thrust bar. As throttle position and actual thrust exceeded 50%, the thrust bars were coded amber. The red line indicated an engine out of tolerance condition, which could occur if actual thrust exceeded 100%. In operation, when a different airspeed was called for, the triangles moved to the new required thrust, the pilot moved the thrust levers to match the triangles with the outer part of the thrust bars. Following an appropriate interval, the remainder of the thrust bar (actual thrust) came to the indicated level.

The engine flame (E) was normally cyan. When the engine was in afterburner, the cyan shape turned amber with a large cyan outline around it. Fuel flow (F) was represented by cyan open arrows entering the engine body shapes. Amount of fuel flow was represented pictorially by the level of cyan fill in the arrows and numerically in pounds per hour. Oil pressure (G), oil quantity (H), and EGT (I) were shown as necessary during engine malfunctions. Normally these quantities were not shown. Engine emergencies and the formats which support them are discussed in Paragraph 5.3.

4.7 Fuel System

The pilot could request fuel status information at any point during the flight by selecting the FUEL switch under the left MPD. This brought up the current fuel status format. Figure 4.7-1 identifies the primary elements of the fuel system. The basic fuel system was pictorially represented as seven tanks (two wing tanks, two inboard tanks, and three centerline tanks) superimposed on an ownship plan view. The fuel contained in a tank was shaded cyan; empty portions of a fuel tank were shown in cyan outline. A normally functioning fuel system consumed fuel in an orderly manner: two wing tanks were the first to be depleted, followed by the two inboard tanks and the centerline tanks. Fuel flow was maintained through a series of valves, transfer pumps, and boost pumps. Valves and pumps were displayed by exception, i.e., those operating normally were not shown. Closed valves appeared as circles with straight lines perpendicular to the fuel line. The four transfer pumps were represented by small white outline triangles. One transfer pump was located in each of the two inboard tanks; the remaining two in the centerline fuel tanks. The two boost pumps, the larger white outline triangles, fed fuel into the engines. The maximum fuel load was 17,000 pounds.

4.8 Electrical System

The pilot could request electrical status at any point during flight simulation by selecting the ELEC switch which brought up

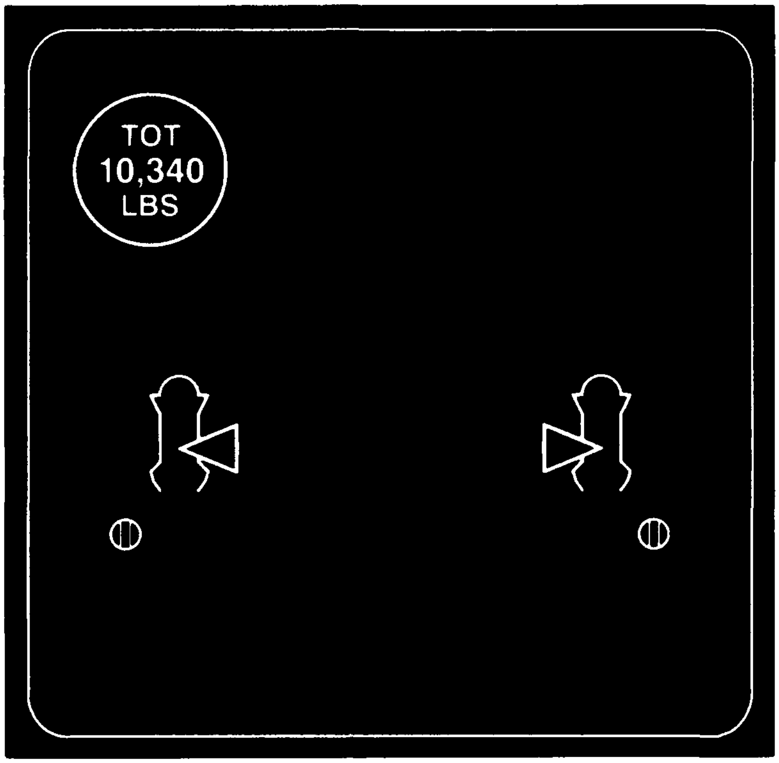


Figure 4.7-1. Fuel Status Format

the current status format on the left MPD. The electrical status was presented as a high level schematic of the primary elements. Each element was abbreviated in the format and could be distinguished by shape (Figure 4.8-1). In a normally functioning electrical system, the five buses and system elements were in the white outline form.

4.9 Hydraulic System

The pilot could obtain hydraulic status information at any point during a mission by selecting the HYD switch which brought up the current status format on the left MPD. The hydraulic status format (Figure 4.9-1) pictorially presented the major elements supported by four hydraulic subsystems. The aircraft provided redundant power for the flight critical elements, i.e., the canards, leading edge flaps, rudders, elevons, and thrust nozzle doors. Non - flight critical elements, i.e., the canopy release, gun drive, nose wheel actuation, nose wheel steering,

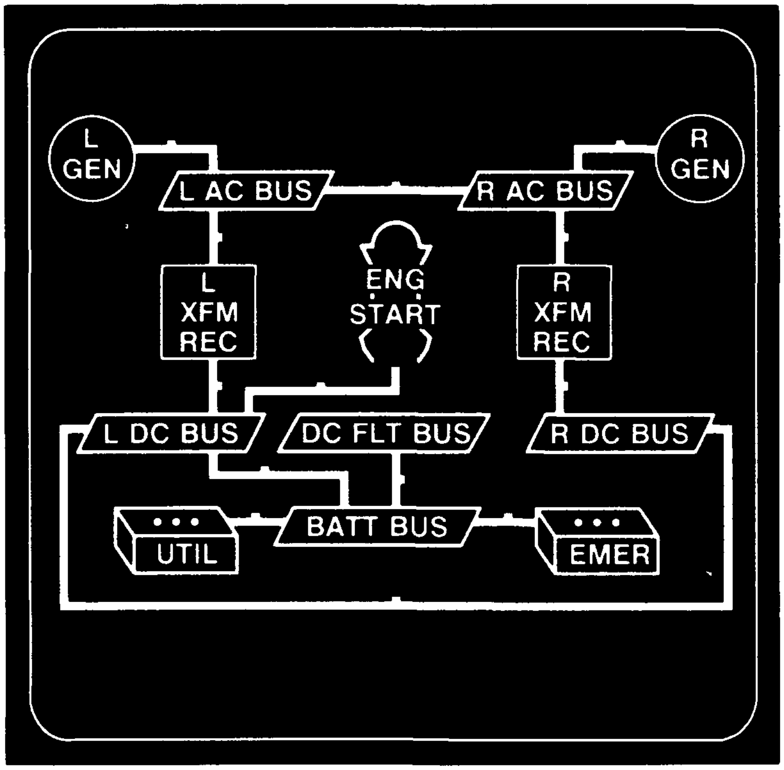


Figure 4.8-1. Electrical Status Format

main landing gear actuation, and aerial refuelling probe, were not redundantly powered.

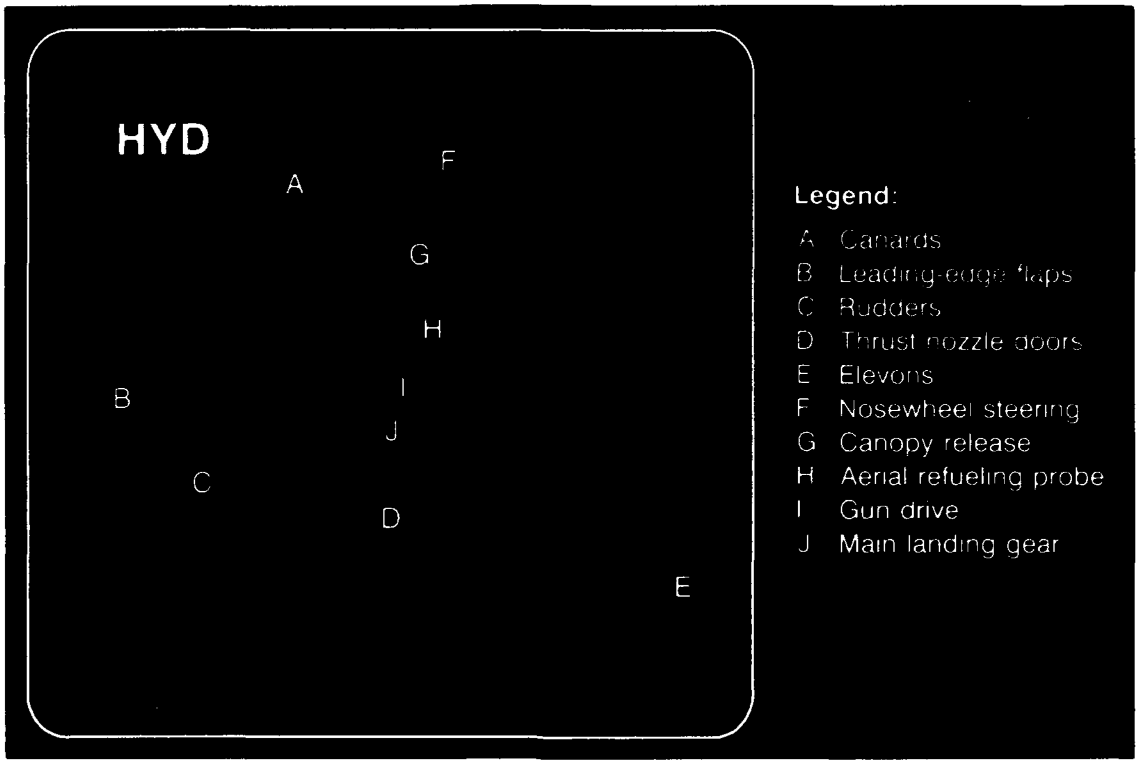


Figure 4.9-1. Hydraulic Status Format

5.0 CREW ALERTING SYSTEM

There were two levels of alert: caution and warning. A caution was generally a lower level alert and was coded amber. A warning was a higher level alert and had red coding. If a failure or malfunction occurred in one of the airplane systems, the crew alerting system informed the pilot in several ways. When an alert condition arose, the master caution light illuminated; in the HUD, the heading box, altitude box, airspeed box, and airplane symbol turned amber or red as appropriate. In addition, the related elements of the Crew Alerting and System Status format flashed amber or red.

5.1 Crew Alerting and System Status Format

The Crew Alerting and System Status (CASS) format (Figure 5.1-1) was displayed full time on the right MPD. CASS had several purposes: it provided full time dynamic display of fuel quantity and engine thrust; it alerted the pilot to system

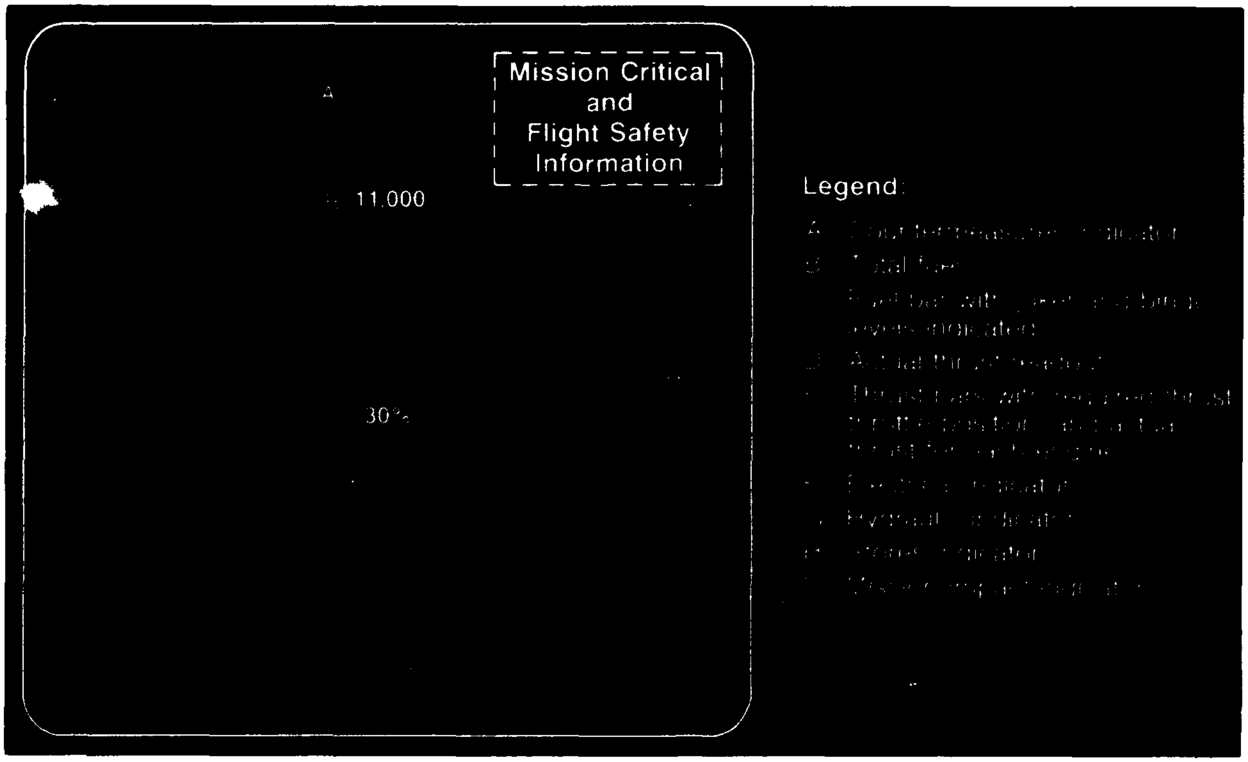


Figure 5.1-1. Crew Alerting and System Status Format

malfunctions; and it identified mission or flight safety implications of those malfunctions.

Near the center of the format was a column representing total available fuel. This amount was also shown numerically just above the column. JOKER and BINGO fuel levels were marked on the column as well. The fuel column was normally colored cyan. It turned amber as JOKER level was reached and red at BINGO fuel level. Below the fuel column was one showing engine thrust. It showed thrust from each engine the same way the engine status format did, i.e., the fill was normally cyan and turned amber or red as appropriate. The single numeric thrust readout was a composite of the two engines.

In its crew alerting function, the CASS format distinguished between caution and warning, indicated which airplane system triggered the alert, and showed mission impact. In addition to the fuel and engine symbology, the countermeasures, electrical, hydraulic, and stores systems were represented. If a malfunction occurred the outline of the symbol representing the affected system turned amber for a caution, or red for a warning. The outline also flashed at a 4 Hz rate.

The five mission impact symbols are shown in Figure 5.1-2. These represented aspects of mission success or airplane performance affected by malfunctions or shortages. They were displayed as appropriate in the upper right corner of the CASS format and indicated immediate or potential limitation on effectiveness. The five impact symbols, coded amber or red as appropriate, were:

1. NO IMMEDIATE IMPACT. The note indicated that current mission objectives could be pursued without limitation but that there was potential for a more serious problem later.

2. WEAPON DELIVERY. The symbol indicated a limitation which reduced some aspect of weapon delivery capability.

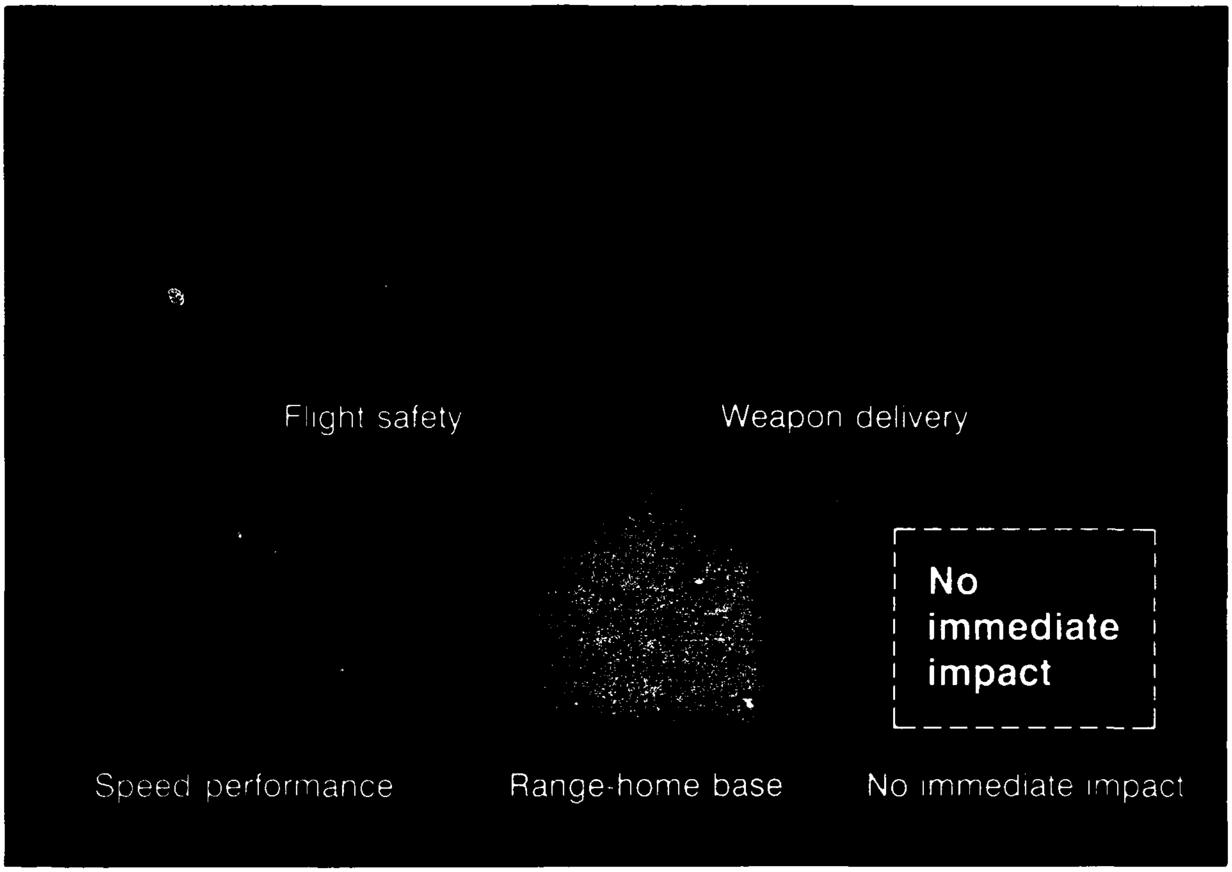


Figure 5.1-2. Mission Impact Symbols

3. SPEED/PERFORMANCE. The aircraft symbol indicated a reduction of top speed or limitation of some aspect of aircraft performance.

4. RANGE/HOME BASE. The symbol indicated a limitation of range capability, and in the extreme, signaled an immediate return to home base.

5. FLIGHT SAFETY. A parachute identified a malfunction so extreme that, unless immediately remedied, would require abandonment of flight.

5.2 Crew Alert Examples, Low Expendables

The pilot had two types of crew alert exercises in this simulation: low expendables and system malfunctions.

indications and required responses were similar. The difference was that, while malfunctions reset to normal after a pilot report, low expendable conditions continued to be displayed.

5.2.1 Low Chaff or Flares

As chaff and flares were expended in response to missile launches against ownship, there could come a point when the level of one or both countermeasures reached a 25 percent threshold. This triggered a chaff or flares warning with amber indications on the HUD, the master caution light and a flashing amber countermeasures symbol on the CASS format. The impact note, on the CASS format was NO IMMEDIATE IMPACT in amber. The word CHAFF or FLARES on the stores and countermeasures status format were amber and two rows of chaff or flares remained in the appropriate dispenser.

The pilot response for this condition was to cancel the master caution, then report the affected system, the problem, and the impact: "countermeasures system, chaff (or flares) low at 25%, and no immediate impact".

5.2.2 JOKER and BINGO Fuel

The two annunciation levels for fuel were JOKER and BINGO levels. BINGO was defined as the amount of fuel required to leave for home base immediately with appropriate reserves. JOKER was an earlier warning level and served as an annunciation to the pilot that he needed to start watching fuel. Normally these levels would be calculated and set by the pilot. In the simulation, they were preset.

As JOKER fuel level was reached, it triggered a caution alert with amber indications on the HUD, the master caution light, and amber indications on the CASS format. The NO IMMEDIATE IMPACT symbol was displayed in amber. On the fuel status format, the digital total fuel readout was coded amber. The pilot response for the JOKER condition was to cancel the master caution, then report the system, the problem and the impact: "fuel system, fuel low at JOKER level, and no immediate impact". The pilot was to break from the threat environment, engage the capture pathway if necessary, and egress.

As BINGO fuel level was reached, it triggered a warning alert with red indications on the HUD, the master caution light, and red indication on the CASS format fuel system symbol. The range/home base impact symbol was displayed in red. On the fuel status format the digital total fuel readout was coded red. The pilot response for the BINGO condition was to cancel the master caution, then report the system, the problem and the impact: "fuel system, fuel at BINGO level, and range/home base impact". The pilot was to engage the capture pathway procedure immediately and egress.

5.3 Crew Alert Examples, System Malfunctions

The general form of indications and pilot actions for system malfunctions was the same as that for the low expendables. Exceptions are noted in the following.

5.3.1 Engine Failure

If an engine flamed out, the HUD alerts were red, the master caution light illuminated, engine symbol outline on the CASS format flashed red, and the CASS showed the red speed/performance impact symbol. On the engine status format, the flame extinguished on the affected engine, thrust dropped to zero, and a red border surrounded the format. The pilot's report: "propulsion system, left (or right) engine out, and speed/performance impact".

5.3.2 Engine Subsystem Malfunctions

In the event of a minor engine subsystem failure, the pilot saw amber alerts in the HUD, the master caution illumination, amber outline on the CASS format engines symbol flash and an amber NO IMMEDIATE IMPACT note. The problems were identified on the engine status format. An example of the report: "propulsion system, left engine low oil pressure, and no immediate impact."

5.3.3 Fuel System Failures

If there was a minor fuel system problem, there were amber alerts on the HUD, the master caution light came on, the fuel indicator on the CASS format flashed amber, and the CASS impact symbol indicated range/home base in amber. The problem was identified on the fuel status format. If, for example, a transfer pump failed, its symbol was displayed in amber on the fuel status format. The pilot's report: "fuel system, forward transfer pump failure, and range/home base."

5.3.4 Hydraulic System Malfunctions

The hydraulic system simulated here had four subsystems. Each provided hydraulic power to a number of single source actuators and dual source actuators. Thus, if one hydraulic subsystem failed, some functions were lost and other critical functions lost their redundancy. If a second subsystem failed, more single source functions went out and some of the critical dual-powered functions could be lost as well.

If a single hydraulic subsystem failed, the pilot saw amber alerts in the HUD, the master caution light came on, and the CASS format showed a blinking amber hydraulic system symbol and one of the impact symbols. The hydraulic status format identified the failed subsystem (1A, 1B, 2A, or 2B) in an amber disk and some single source elements were shown in solid amber indicating their loss. Other elements showed amber bars indicating loss of redundant power. An amber caution border surrounded the format. The pilot's report: "hydraulic system, single subsystem failure affecting the ____, ____, and ____ with no immediate impact".

If two hydraulic subsystems failed and some of the flight critical elements lost both sources of hydraulic power, the pilot saw red alerts on the HUD and the master caution light. The CASS format flashed a red hydraulic system symbol and displayed one of the impact symbols in red. The hydraulic status format named the failed subsystems in red disks, showed lost single source elements in solid amber, showed loss of flight critical elements with solid red fill, and had a red border. The pilot's report: "hydraulic system, subsystem failure affecting the ____, ____, and _____, with flight safety impact".

5.3.5 Electrical System Malfunctions

If there was an electrical system problem, the pilot saw amber alerts on the HUD, the master caution light illuminated, and the electrical system symbol on the CASS format flashed amber. The impact note was NO IMMEDIATE IMPACT in amber. The electrical status format had an amber border and the malfunctioning element was colored amber. The pilot's report: "electrical system, failure of the ____, ____, and ____ with no immediate impact".

6.0 STATUS FORMAT TEST

The test reported in this section had a limited objective: evaluation of the use of retinal disparity in the status formats. If disparity had operational value with these status formats, it would reduce the time required for pilots to understand a display and reduce errors in interpretation. The status format test was designed as an experimental test of those hypotheses. This experiment consisted of two shared tasks: tracking a director element in a head-up display (HUD) and responding to information on a status format displayed head-down.

Two of the status formats were used. As discussed in paragraph 4.8, the electrical status format is a top-level schematic drawing of the airborne electrical system. One of four system elements would malfunction and the pilot's task was to press a button next to the malfunctioning element. Disparity was added in some conditions to help highlight the malfunctioning element.

The sensor coverage format, discussed in paragraph 4.3, was somewhat different - a "wire globe" surrounding a stylized airplane. The globe and plane were viewed from behind and above. The globe was divided into eight segments, any one of which could malfunction. The displayed meridians and parallels in the failed segment of the globe turned amber.

These two formats were taken to represent the entire class of status formats. Each is an example of one of two uses of disparity. In the electrical status format, disparity was added to highlight a failed system element in an otherwise flat picture. The sensor coverage format used disparity to add depth to the "wire globe", presumably helping the pilot make the fore-aft distinction.

6.1 Hardware Configuration for the Status Format Test

Figure 6.1-1 is a schematic diagram of the equipment used in the status format test. Event control, HUD target movement and data recording were done by the Gould SEL 32/9750 host computer. The HUD symbols were supplied by one Megatek graphics generator and the status formats by another. A Stereographics display controller, on-screen shutter and polarized glasses were used to create the 3-D image for the status formats. Figure 6.1-2 shows the subject's station.

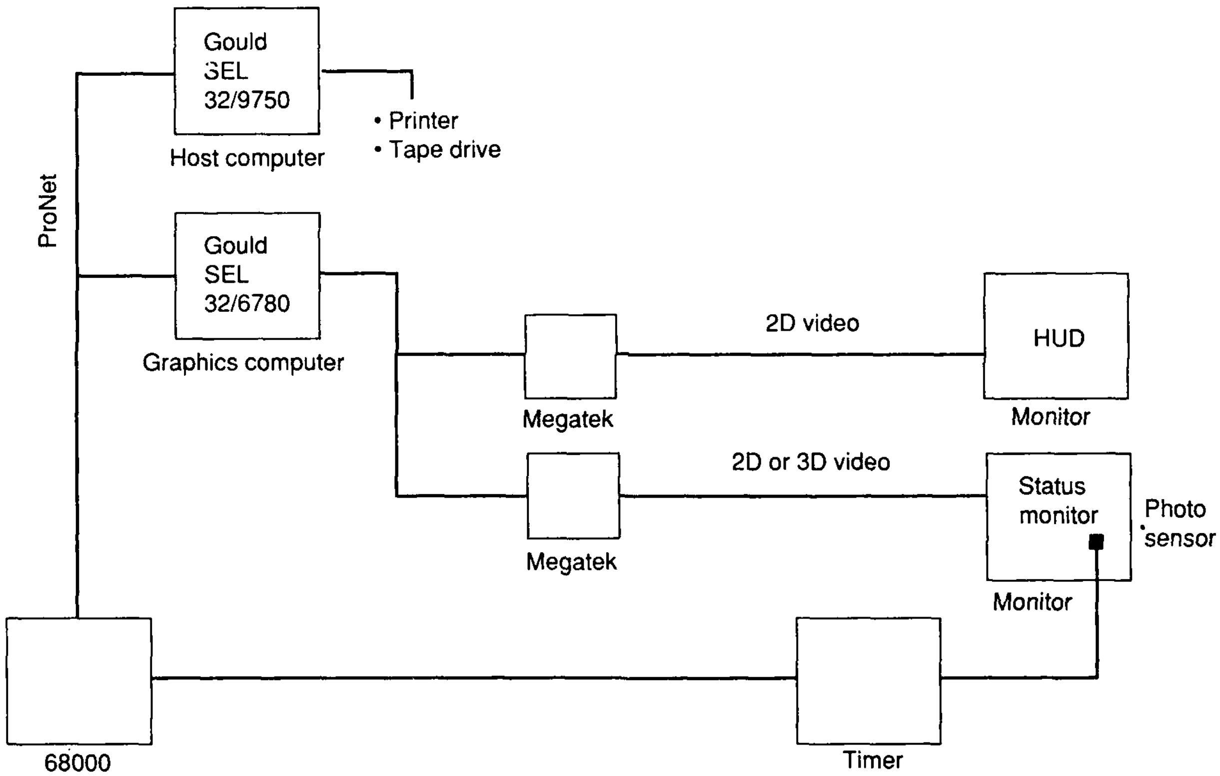


Figure 6.1-1. Status Format Test Hardware Configuration

A special timing circuit was designed and built to sense stimulus format appearance on the screen using a light sensitive element mounted unobtrusively near one corner of the status display. When a status format was displayed, this element sensed the amber border and started a clock which stopped when the subject responded. This arrangement measured response time in milliseconds, independent of the small temporal uncertainties

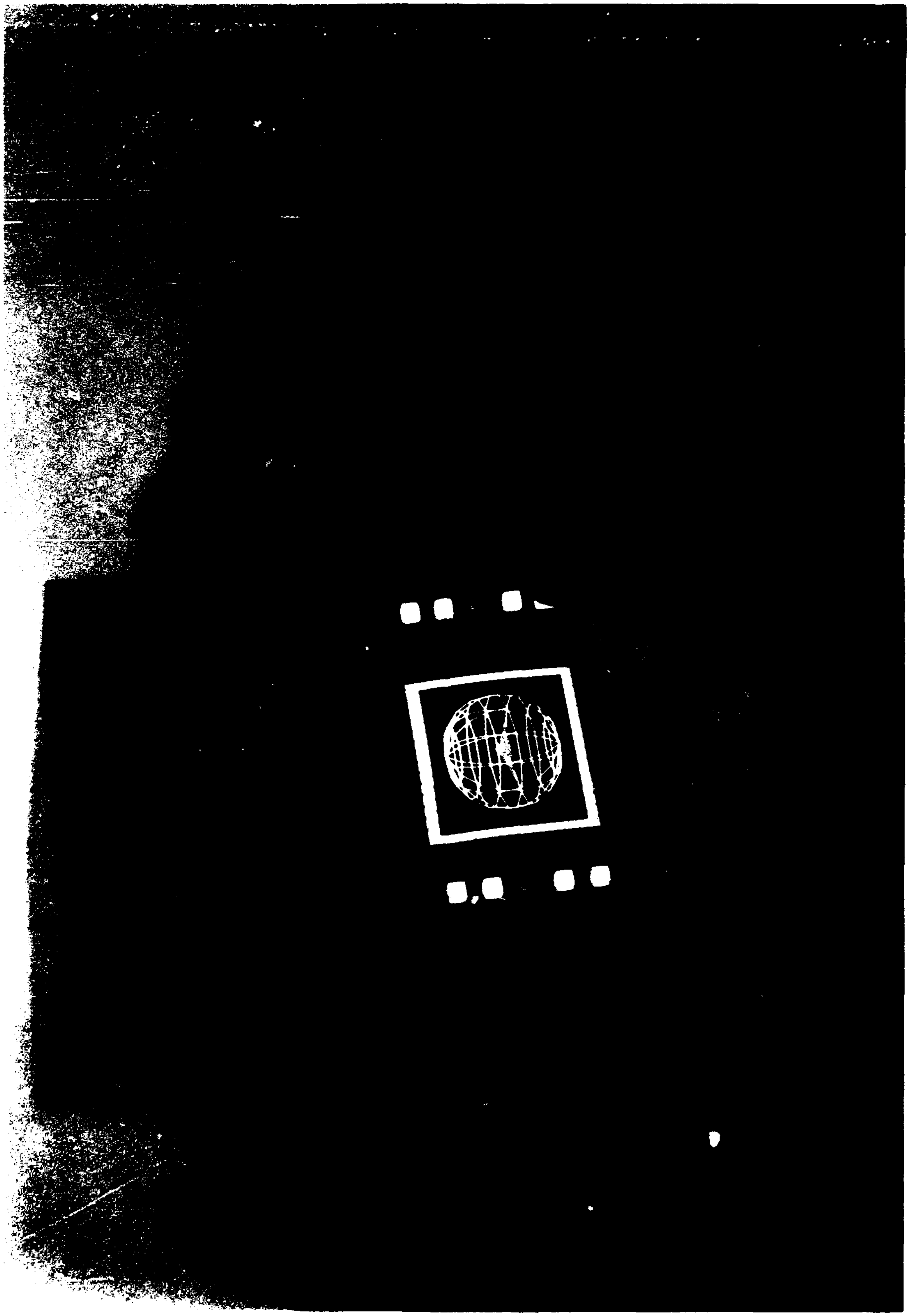


Figure 6.1-2. Subject's Station

occasioned by asynchronous serial operation of two computers, a graphics generator and the display.

6.2 Test Formats for the Status Format Test

Three formats were used in this study. The HUD provided the stimulus for the secondary tracking task. The electrical status and sensor coverage formats were the test stimuli for the concurrent response time task.

6.2.1 Head-Up Display

Figure 6.2-1 shows the HUD used in this test. Compared with the HUD used in the main study, this was very simple, consisting of only two elements, a fixed velocity vector symbol and a moving tracking dot. During the test trials both symbols were colored cyan on a black background. Before a session and between blocks within a session, they alternated cyan and amber. After a session, they were steady amber. Retinal disparity was not added to the HUD. Movement of the tracking dot was controlled by two summed, asynchronous sine waves in the vertical direction and two in the horizontal. The result was random-appearing movement and a degree of difficulty which was easily mastered by the subject pilots but which still required a moderate level of concentration.

6.2.2 Electrical Status Format

Figure 6.2-2 shows the electrical status format used in the response time task. There was a broad amber band around the outside of the format and the system elements were drawn in white. On each trial, one of the four corner elements: left generator, right generator, utility battery, or emergency battery were shown as having malfunctioned. The malfunctions were indicated one of three ways: with amber color, with 8 mm of added retinal disparity or with both color and disparity. As

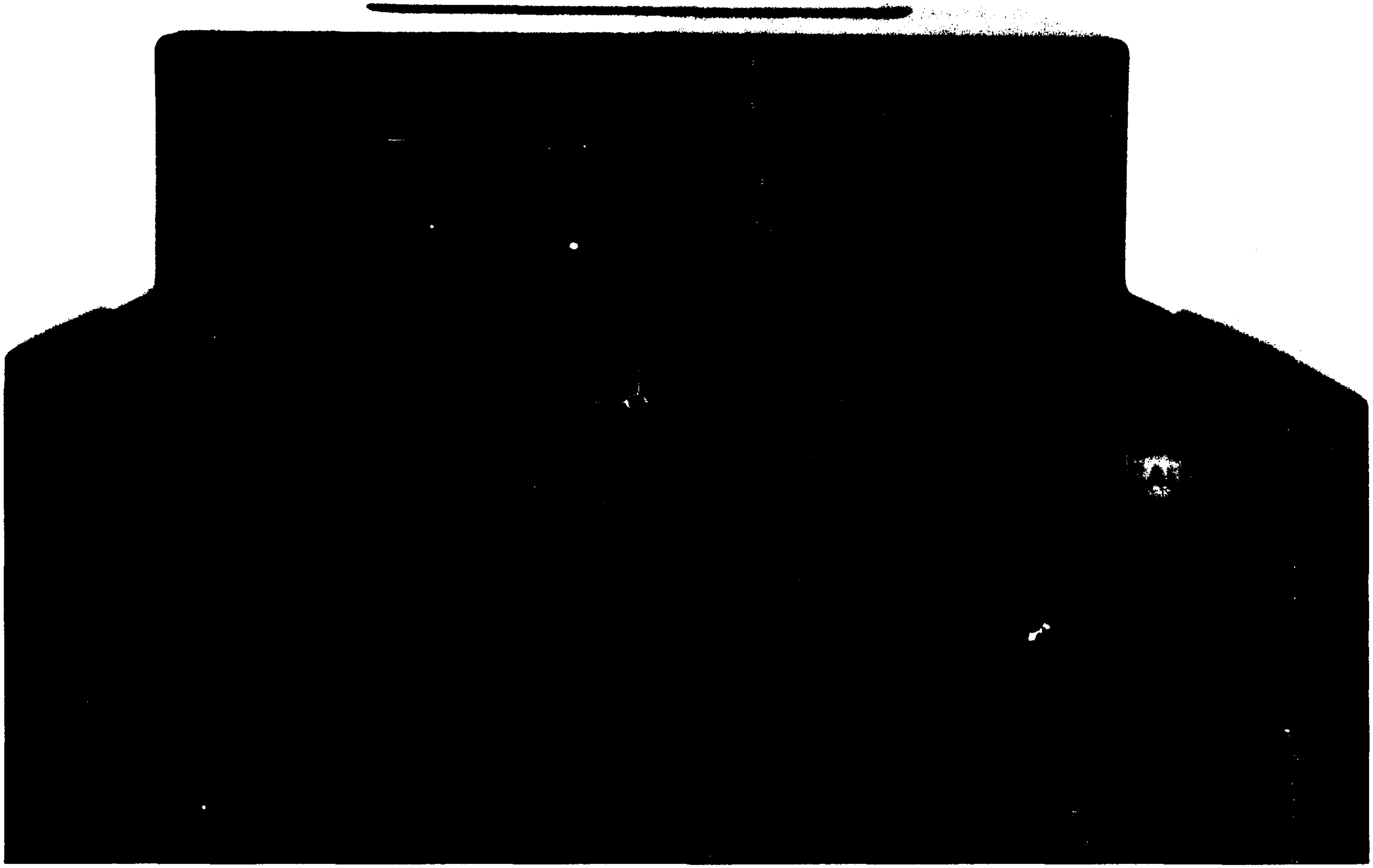


Figure 6.2-1. Head-Up Display

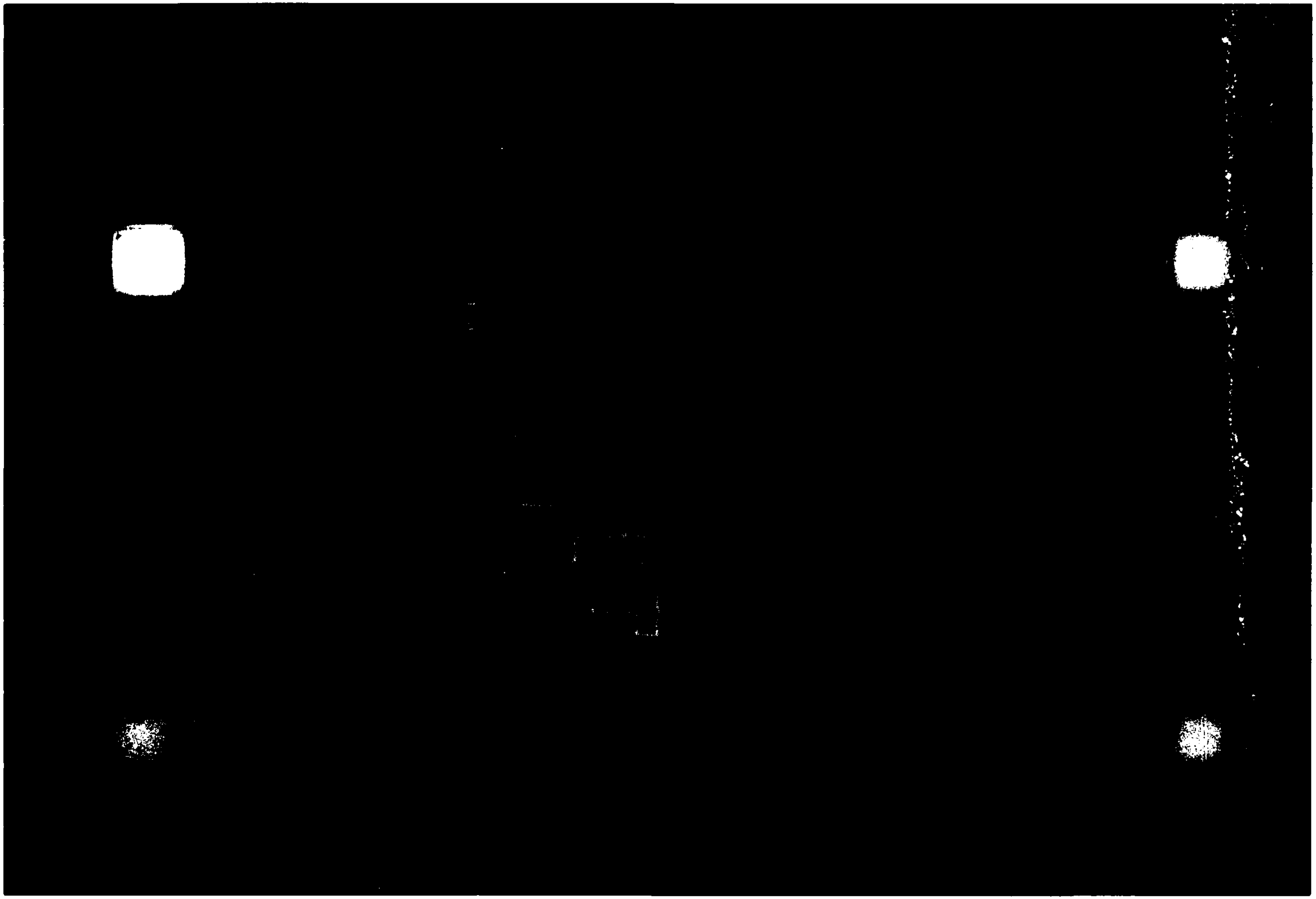


Figure 6.2-2. Electrical Status Format

the figure shows, each of the four malfunctions had an associated response button.

6.2.3 Sensor Coverage Format

Figure 6.2-3 shows the sensor coverage format used here. It showed a cyan airplane centered in a white "wire globe". The airplane and globe were viewed from above and behind. The equator and meridians of the globe divided it into eight segments representing eight sectors of sensor coverage. On each trial, one of the sectors was bad and its "wires" were colored amber. There was a broad amber border around the format. Each of the eight potentially failed sectors had a response button associated with it as shown in the figure. The sensor coverage format was shown in two conditions: with and without added retinal disparity. In the disparity condition, depth in the globe was enhanced by continuously varying disparity from 6 mm into the screen for the extreme far side to 6 mm toward the observer for the extreme near side.

6.3 Conduct of the Status Format Test

In order to provide a sensitive test of what was suspected to be a relatively subtle effect, this experiment was conducted as a closely controlled response time test with a secondary tracking task.

6.3.1 Subjects

The six subjects were all former military pilots, with from 850 to 5600 hours of flight time (mean was 3025 hours). None were current in any operational military aircraft. They all claimed 20/20 vision, corrected if necessary, at cockpit distances. None admitted to any color defect and all passed the three parts of the stereo-fly test (Stereo Optical Co., Chicago), all showing stereoacuity down to 40 seconds angle of stereopsis.

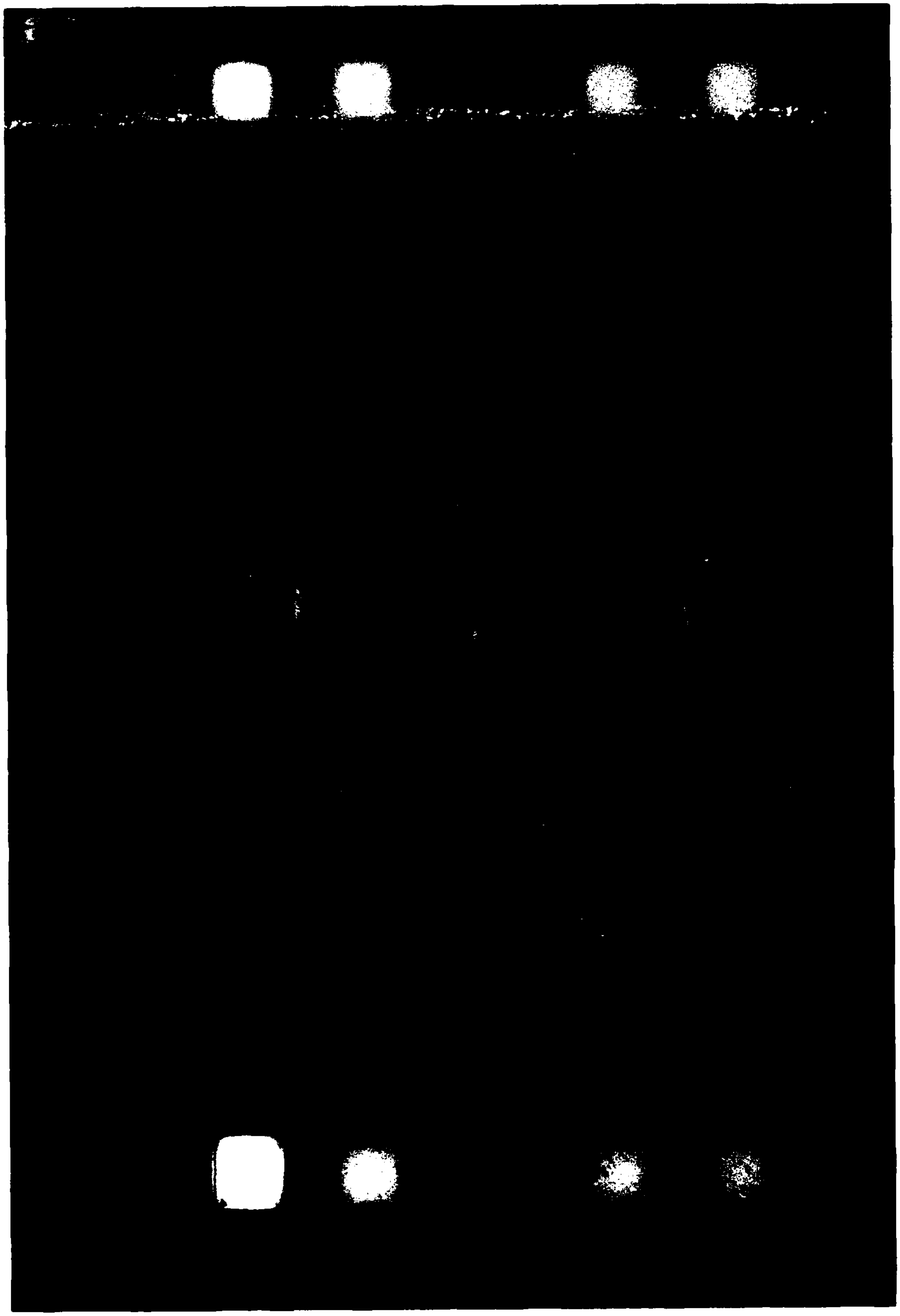


Figure 6.2-3. Sensor Coverage Format

Subjects wore polarized glasses throughout their training and testing sessions.

6.3.2 Experimental Design

The status format experiment was organized as a test of two hypotheses. That is, the electrical status format was used to test the hypothesis that added stereopsis would make displayed elements more noticeable and the sensor coverage format was used to test the hypothesis that stereopsis would enhance perception of a three-dimensional object. The two formats were used and the two hypotheses tested in the same sessions with the same subjects. The experimental design is illustrated in Figure 6.3-1.

The electrical status format was tested with a 6x3x4x3x2 design. These were the six subjects described in paragraph 6.3.1, the three display conditions and four failed elements described in paragraph 6.2, three intertrial intervals (7, 11.5 and 16 seconds) and two replications. The intertrial intervals were selected to allow the subject time to recover from the previous trial but to be uncertain when the next would occur. Within each block, failed elements and intertrial intervals were randomized with the constraint that each element-interval combination appear exactly twice in a 24-trial block.

The sensor coverage format was tested with a 6x2x8x3 design. There were the same six subjects, two display conditions, eight failed elements and three intertrial intervals. Within each block, failed elements and intertrial intervals were randomized with the constraint that each element-interval combination appear exactly once in a 24-trial block.

6.3.3 Schedule and the Subjects' Tasks

The testing was accomplished over a two-week period. Each subject participated alone in seven sessions. The first session

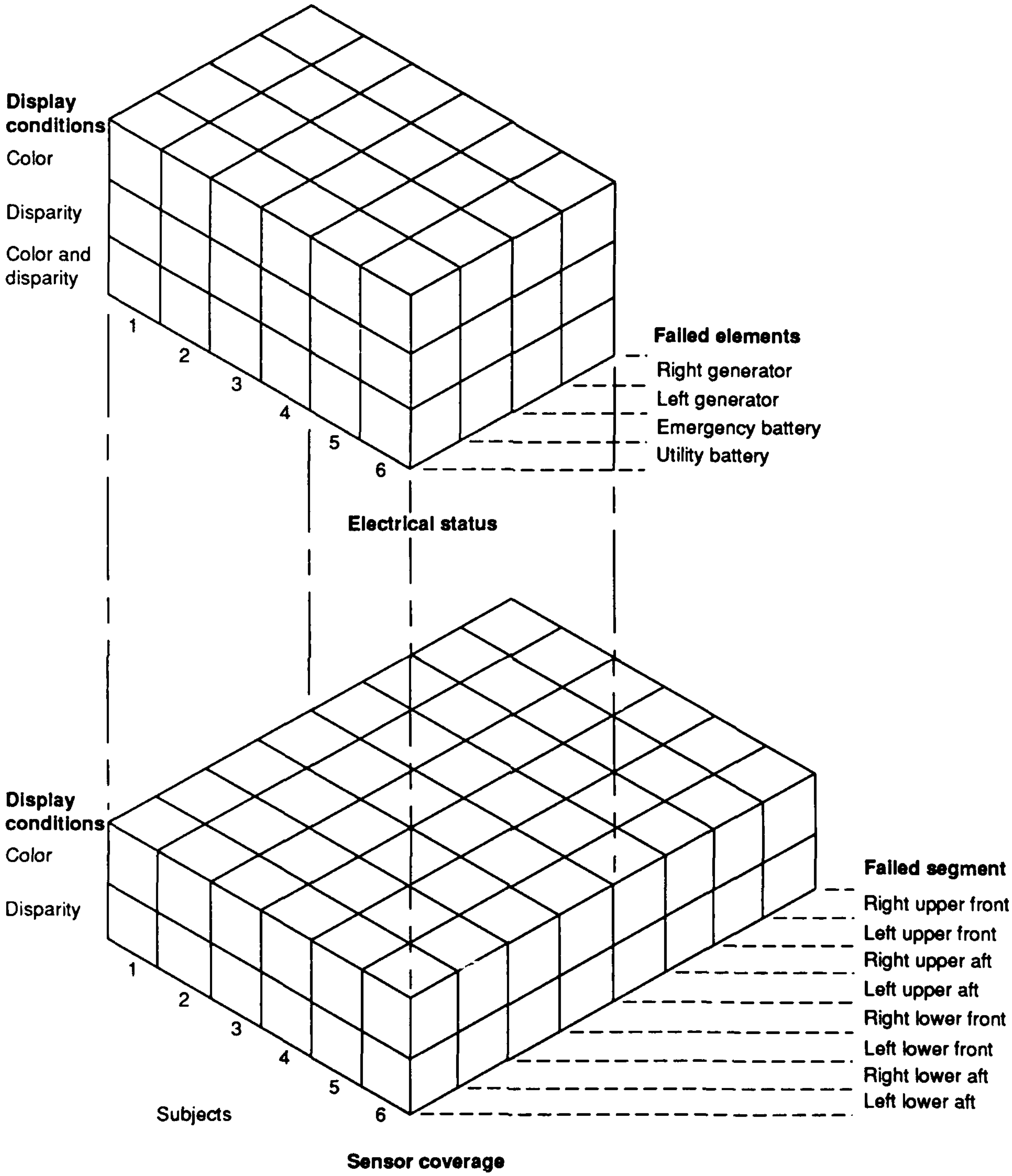


Figure 6.3-1. Experimental Design

was for training; data collected in the remaining six sessions were included in the analysis. Because it is difficult for a subject to maintain adequate concentration for long period in these tasks and because a large amount of data was required, the seven sessions for each subject were distributed over three to five days. No subject had more than three sessions per day and sessions were separated by at least one hour.

The subjects were instructed to use the right side flight control stick to fly the HUD airplane symbol to the command dot and to keep the dot centered. They were asked to keep their left forefinger on a mark just below the test display and told that at various intervals, one of the status formats would appear on that display and remain on for 4.4 seconds. They were asked to then quickly and accurately press the appropriate button to indicate which of the system elements had malfunctioned. Figure 6.3-2 is a timeline of one trial.

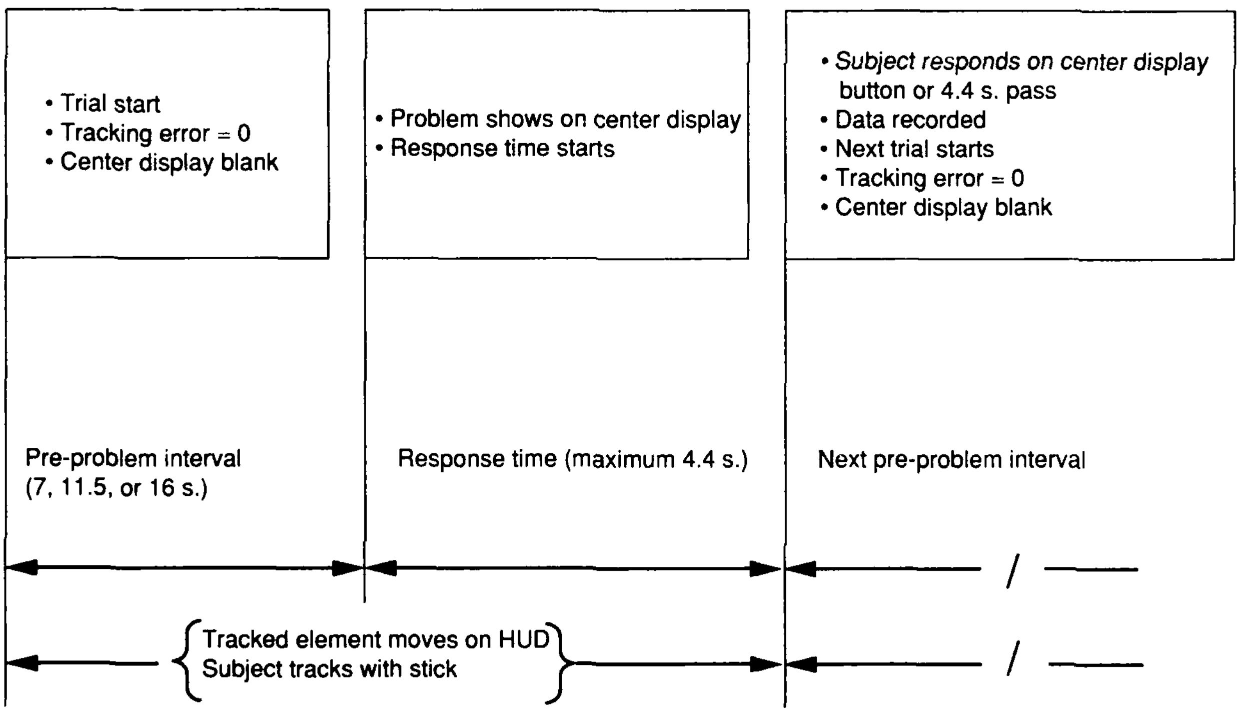


Figure 6.3-2. Trial Timeline (Repeated 30 Times Each Block)

In the training session, subjects first provided the information on their flight experience, visual acuity, color vision and depth perception summarized in paragraph 6.3.1. They then moved to the simulator cockpit and read the detailed instructions. As part of those instructions, the formats, malfunctions and display conditions were shown. Finally, the subjects completed the training session by performing a session of trials structured like their subsequent data sessions would be. The training sessions lasted approximately 75 minutes each.

Each subject's six test sessions followed a similar pattern. They were seated in the simulator and flew five blocks of 30 trials each. The first six trials in each block were considered practice and last 24 were recorded for analysis. Between each pair of blocks was a subject-paced rest period. Most of the subjects gave themselves 15 to 30 seconds rest before beginning the next block. The order of blocks for each subject and session is shown in Table 6.3-1. Note that, within each sessions, the three electrical status blocks were grouped as were the two sensor coverage blocks. The test sessions lasted approximately 40 minutes.

6.4 Results of the Status Format Test

As indicated, the arrangement of this experiment allowed for separate data analyses for the two formats. The results are presented here, first for the electrical status format and then for the sensor coverage format. Within each, tracking data, response time and response errors are treated.

6.4.1 Results with the Electrical Status Format

Root-mean-square error scores in the X and Y directions are plotted in Figure 6.4-1, averaged across subjects. There were no significant differences among the three display conditions: disparity, color, and color with disparity. What is clear in the plot is a significant session effect ($p<.01$) shown by the decrease in RMS errors from Session 1 to Session 5. This can be interpreted as a learning effect. To put the magnitude of

Table 6.3-1. Status Format Test Schedule

Subject	Session	Block				
		1	2	3	4	5
1	1	EB	EC	ED	SB	SC
	2	EC	ED	EB	SC	SB
	3	ED	EB	EC	SB	SC
	4	SC	SB	ED	EC	EB
	5	SB	SC	EB	ED	EC
	6	SC	SB	EC	EB	ED
2	1	SC	SB	EC	ED	EB
	2	SB	SC	EB	EC	ED
	3	SC	SB	ED	EB	EC
	4	EB	ED	EC	SB	SC
	5	ED	EC	EB	SC	SB
	6	EC	EB	ED	SB	SC
3	1	EC	EB	ED	SB	SC
	2	EB	ED	EC	SC	SB
	3	ED	EC	EB	SB	SC
	4	SC	SB	ED	EB	EC
	5	SB	SC	EC	ED	SB
	6	SC	SB	EB	EC	ED
4	1	SC	SB	EB	ED	EC
	2	SB	SC	EC	EB	ED
	3	SC	SB	ED	EC	EB
	4	EC	ED	EB	SB	SC
	5	ED	EB	EC	SC	SB
	6	EB	EC	ED	SB	SC
5	1	ED	EB	EC	SB	SC
	2	EB	EC	ED	SC	SB
	3	EC	ED	EB	SB	SC
	4	SC	SB	EC	EB	ED
	5	SB	SC	ED	EC	EB
	6	SC	SB	EB	ED	EC
6	1	ED	EC	EB	SB	SC
	2	EC	EB	ED	SC	SB
	3	EB	ED	EC	SB	SC
	4	SC	SB	EB	EC	ED
	5	SB	SC	ED	EB	EC
	6	SC	SB	EC	ED	EB

Legend:
ED Electrical, disparity only
EC Electrical, color only
EB Electrical, color with disparity
SC Sensor status, color only
SB Sensor status, color with disparity

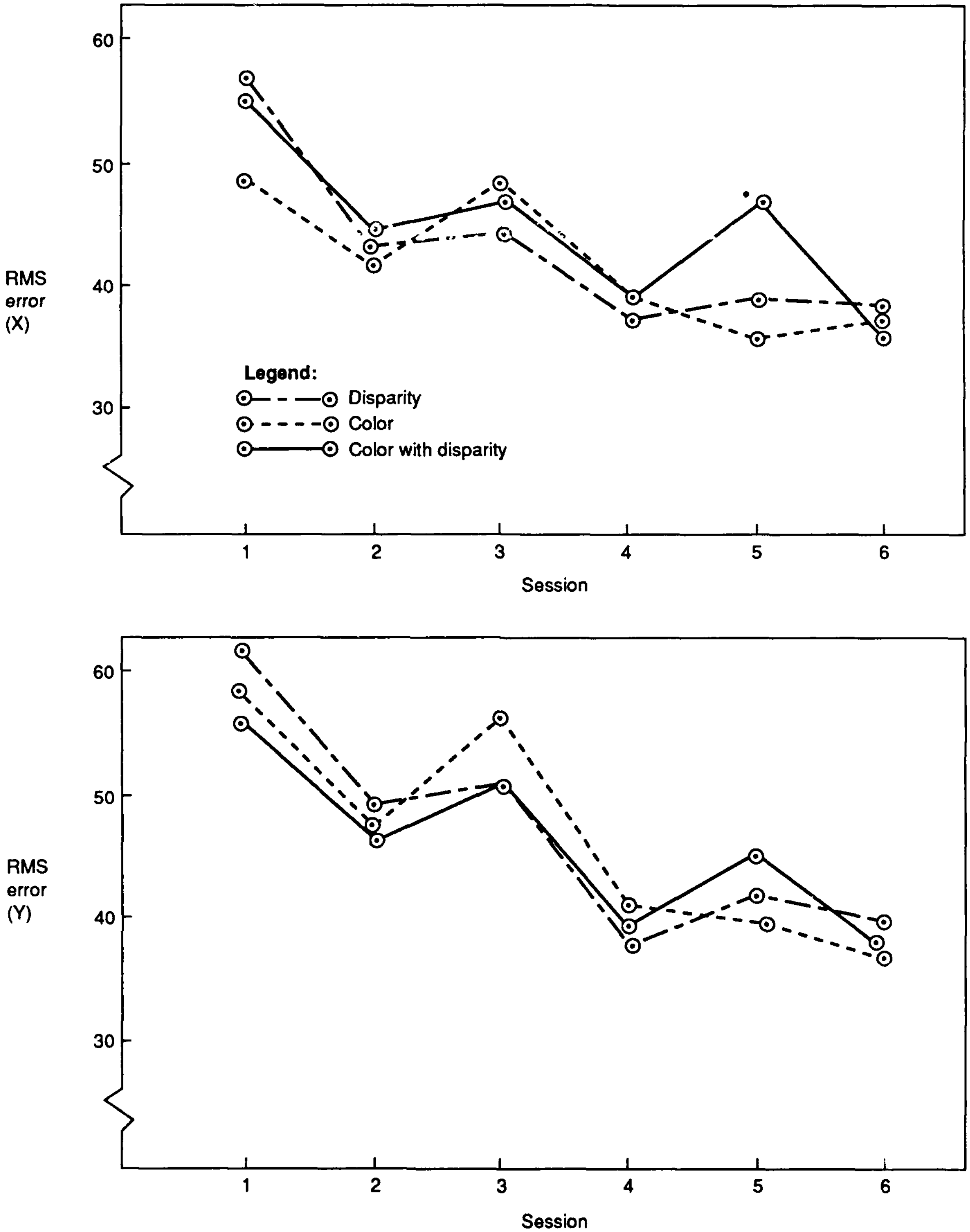


Figure 6.4-1. Tracking Errors With Electrical Status Format

these errors in context, the tracking spot had a diameter of 60 units and the circle in the velocity vector symbol had a 120 unit diameter. (See Figure 6.1-1). So the subjects, even in Session 1, were keeping the ball at least touching the circle.

Mean response times to malfunctions with the electrical status format are plotted in Figure 6.4-2. By analysis of variance,

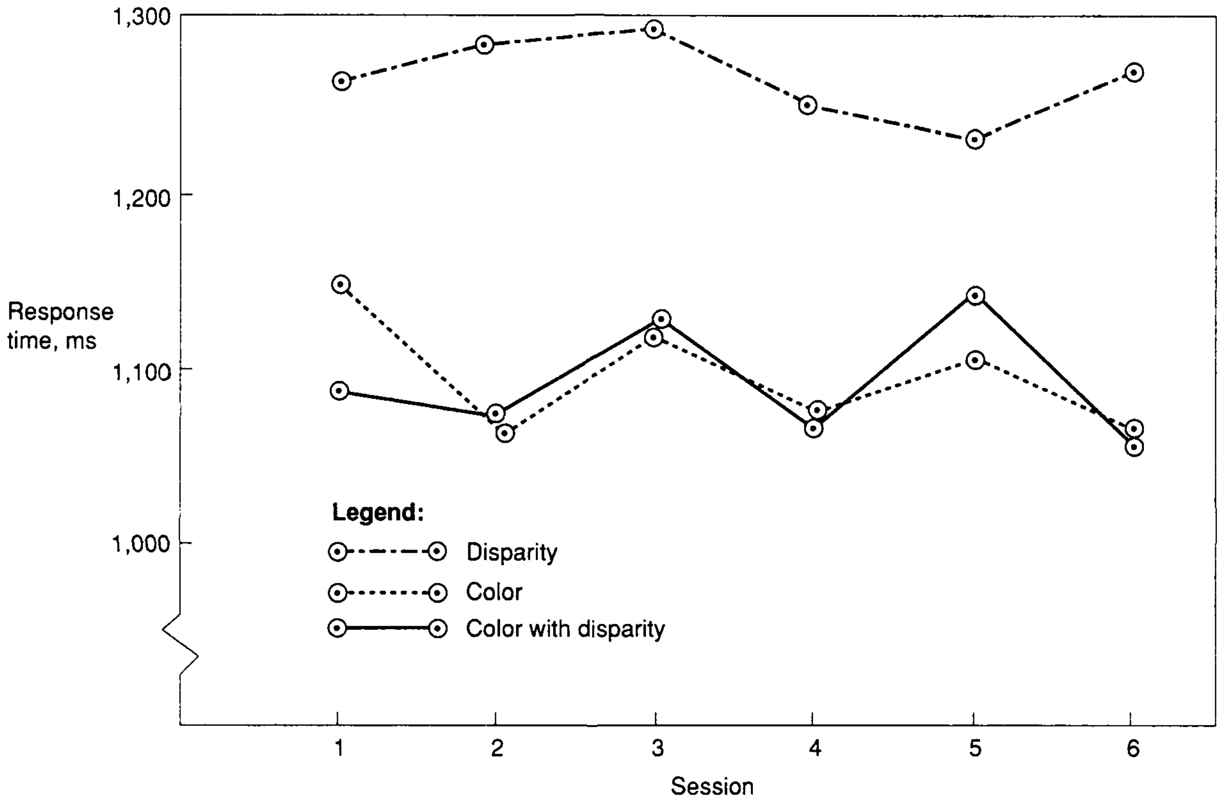


Figure 6.4-2. Response Time With Electrical Status Format

the display condition effect was highly significant ($p<.01$). By Scheffe pair-wise comparison test, the significance lay in the longer mean response time with the disparity only condition (1264 ms). The difference in mean response time between color only (1098 ms) and color with disparity (1095 ms) was not significant. The analysis of variance also showed significant subject, session and intertrial interval effects.

In all, 2592 data trials were devoted to the electrical status format, 864 in each of three display conditions. Of these trials, subjects made the wrong response on 3 trials and failed to respond on 6 trials. Aside from the fact that 8 of these 9 errors were committed by one of the subjects, there is little of interest in the distribution of these errors. The proportion of correct responses was 0.997.

6.4.2 Results with the Sensor Coverage Format

Mean RMS tracking errors in the X and Y directions are plotted in Figure 6.4-3. There is a significant session effect in both directions which can probably be interpreted as learning. There is a small but significant difference between color and color with disparity in both directions. In the X dimension, addition of disparity reduced overall mean RMS error from 46.4 to 44.0 units. The reduction was from 50.1 to 45.8 units in the Y dimension.

Mean response times for malfunction identification with the sensor coverage format are plotted in Figure 6.4-4. Addition of retinal disparity occasioned a significant decrease in response time, from 1679 ms with color only to 1484 ms with color and added disparity. The analysis of variance also identified significant session effects.

In all, 1728 trials were devoted to the sensor coverage format, 864 in each of the two display conditions. Of these trials, subjects made the wrong response on 52 trials and failed to respond on 4 trials. The proportion of correct responses was 0.968.

The error trials were distributed as shown in Table 6.4-1. By the Chi-squared test, there were significantly more fore-aft confusions than the other two error categories ($p<.001$). There were also significantly more total errors ($p<.001$) and fore-aft confusions under the color only condition than than under the color with disparity condition.

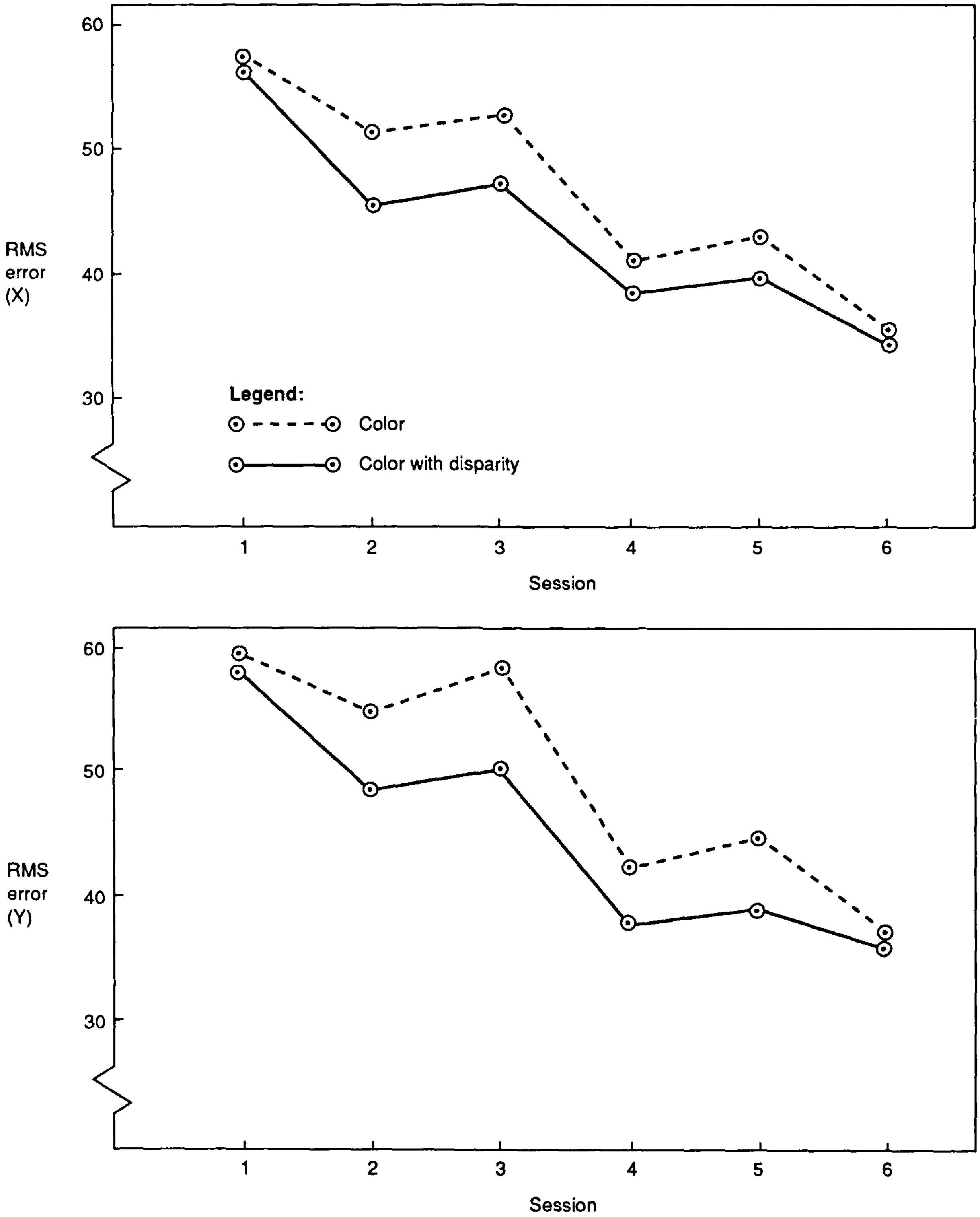


Figure 6.4-3. Tracking Errors With Sensor Coverage Format

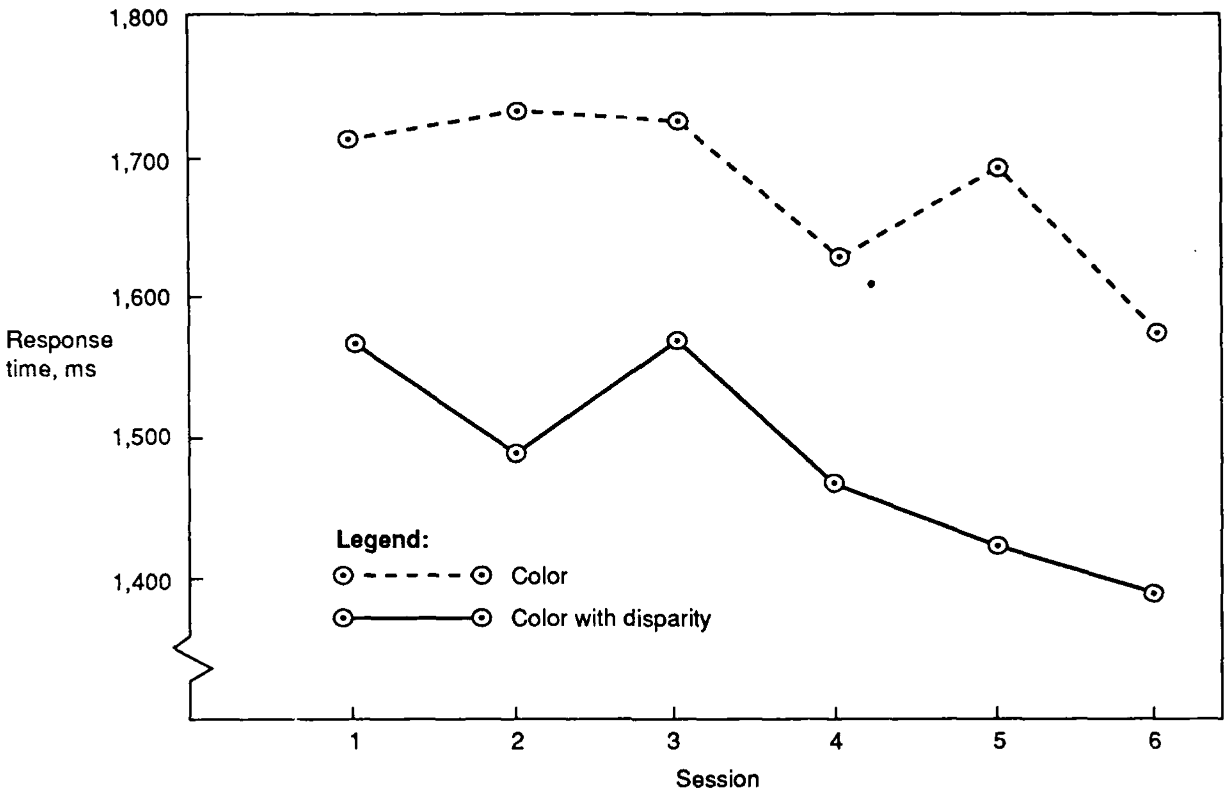


Figure 6.4-4. Response Time With Sensor Coverage Format

Table 6.4-1. Distribution of Errors with Sensor Coverage Format

Display condition			
Error	Color	Color with disparity	Total
Omitted response	4	0	4
Fore-aft confusion	39	11	50
Other error	0	2	2
Total	43	13	56

6.5 Conclusions from the Status Format Test

The subjects' primary task in this experiment was malfunction identification using two status formats. The experimental hypothesis was that stereopsis or retinal disparity would affect response time and errors in malfunction identification.

The electrical status format was naturally a planar display with no depth and so no monocular depth cues. Malfunctioning elements were indicated one of three ways: with disparity, with color or with both. The error data indicate that the malfunctioning element could be identified reliably under all three conditions. Since response time was significantly longer in the disparity only condition than either of the color conditions, it can be concluded that color is much more effective as a malfunction identifier than is disparity. Further, once color is used, adding disparity does not significantly enhance performance.

The results with the sensor coverage format were somewhat different. In that format, disparity was used to enhance the monocular depth cues in modeling a three-dimensional "wire globe". There, when disparity was added, both response time and the number of fore-aft confusion errors decreased. A conclusion from these results is that disparity enhanced the perception of depth (fore-aft dimension) and helped the subjects respond faster and more accurately. Further, the slight but significant decrease in secondary task tracking error under the color with disparity condition may indicate a decrease in workload or resource demand when disparity was added.

Taken together, the results with these two formats suggest that adding retinal disparity may enhance performance by augmenting monocular depth cues, but that it is not an effective replacement for differential color as an attention-getting dimension.

It is recommended that the boundary conditions of this effect be explored before disparity is applied to operational cockpit displays. What sort of formats are enhanced by disparity? What monocular cues or cue combinations are enhanced by added disparity and which are not? How does this effect interact with display spatial resolution or other display characteristics?

Once these and related questions are answered, it becomes an operational question whether the magnitude of the response time decrease (195 ms here) and of the response error rate decrease (4.98% to 1.5% here) are worth the costs of providing the disparity cue.

7.0 CONDUCT OF THE MAIN STUDY

The purpose of the main simulation was to apply the knowledge and skills of operational pilots to assess the pictorial formats and to evaluate the utility of the 3-D treatment for cockpit displays. In this sense, the pilots acted as measuring instruments. This section describes what the pilots experienced in their four days on site. Briefly, there was a ground school, followed by hands-on training. The pilots flew simulated missions where the emphasis was on collection of performance and workload data in a variety of exercises or events.

7.1 Test Subjects

The Air Force Project Engineer arranged for sixteen pilots to serve as subjects in this simulation. All but one were active duty Air Force or Navy interceptor or attack pilots, current in one or more combat aircraft. As Table 7.1-1 shows, a wide range of experience was represented in the subject sample. A handbook (Martin and Way, 1988) was sent to the pilots before they reported for the simulation and all professed familiarity with

Table 7.1-1. Aircrew Qualifications

Pilot	Branch	Total Hours	Current Aircraft	Other Aircraft
1	USAF	1400	F-15	O-2, OT-37, AT-38
2	USN	825	A-6E, KA-6D	T-34C, T-2C, TA-4J
3	USN	1830	A-6	F-14, A-4
4	USAF	1425	F-15	AT-38, T-38, T-37, B-52
5	USN	4300	A-6E	TA-4J, F-18, F-4, T-2C, T-28, T-38, C-172, A-23
6	USAF	3500	F-15	J-3, T-33, T-37, T-38
7	USN	1670	A-6E, KA-6D	TA-4, T-2B
8	USAF	860	F-15	AT-38, T-37
9	USN	1600	A-6E	TA-4J, T-2C, T-28B
10	USAF (Ret.)	2000	None	F-4, F-16, OV-10
11	USN	1400	A-6E	A-4, T-2, T-34C
12	USN	1800	A-6	T-2, A-4
13	USN	600	A-6E	T-34C, T-2C, TA-4
14	USAF	1400	F-15	T-37, T-38, F-4
15	USN	750	A-6E	T-34C, T-2, TA-4
16	USAF	1150	F-15	T-37, T-38, OA-37

its contents when they arrived. Each pilot was given the stereo fly test (Stereo Optical Co., Chicago) and each demonstrated stereoacuity to 40 seconds angle of stereopsis.

7.2 Mission Types

Pilots flew two different mission types: air-to-ground and beyond visual range (BVR) air-to-air. Events and exercises peculiar to a given mission were separated in time so one activity was completed prior to beginning the next. There were eight practice and four test missions in each set. Appropriate performance measures were collected and, at the end of each set, crews were debriefed on the formats used in that set.

Figure 7.2-1 is a sketch of the gaming area showing the nominal flight route, the terrain which governed that route and the forward-line-of-troops (FLOT). Air-to-ground missions were flown through this environment and the BVR missions were flown over it.

7.2.1 Air-to-Ground Missions

The air-to-ground mission objective was to penetrate, at low level, a heavily defended area to destroy a ground target while minimizing exposure to ground threats. While in low level flight, the pilot had the option of deviating from the planned flight route through a number of valleys, to avoid displayed SAM and AAA sites. Expendable countermeasures, jamming, and antiradiation missiles were available for self defense. Offensive weapon delivery of guided bombs occurred during the mission. There were eight different air-to-ground missions, four for practice and four reserved for the test sessions.

7.2.2 Air-to-Air Missions

The air-to-air mission objective was to engage, at beyond-visual-ranges, air targets of various types, numbers, and

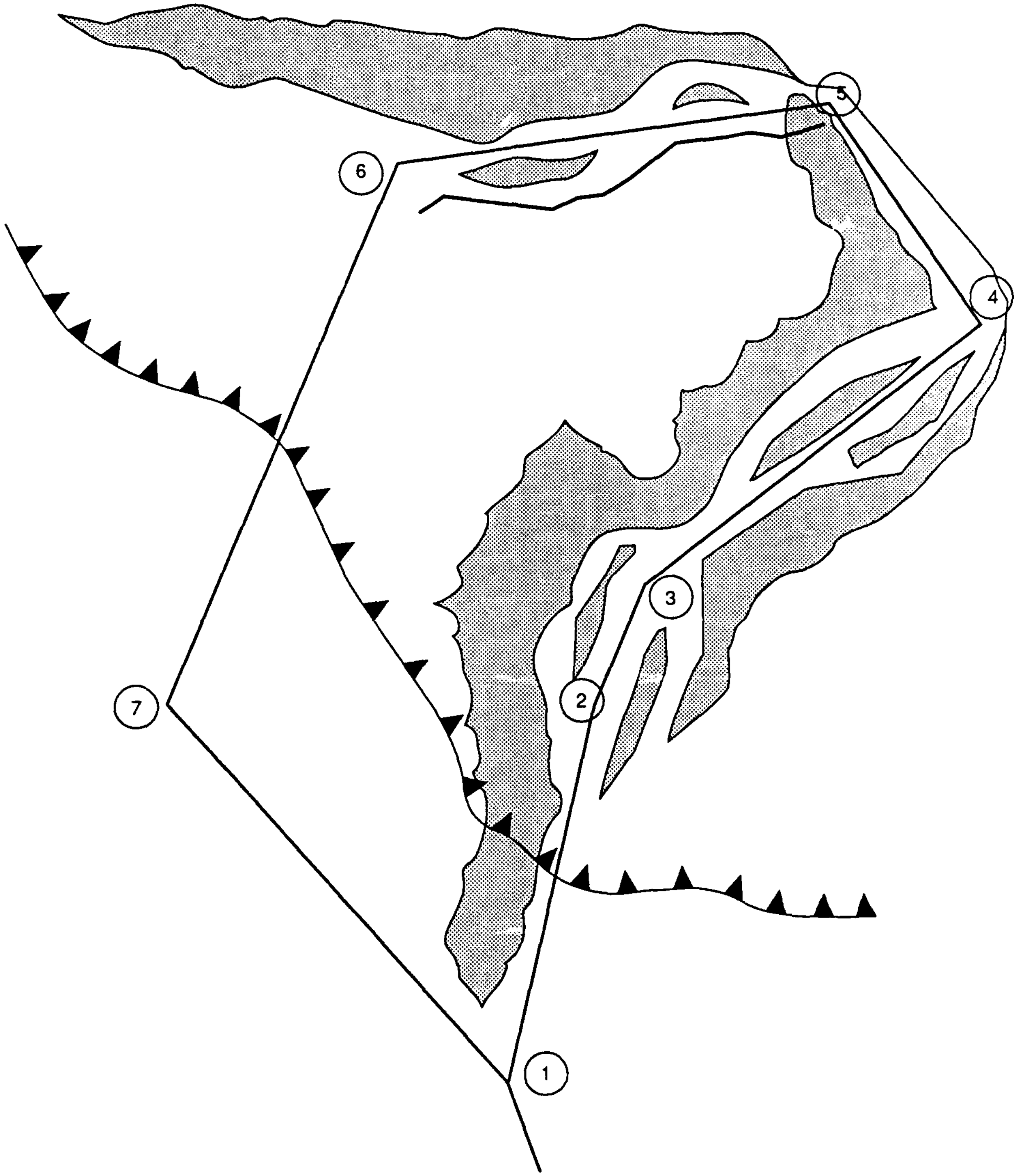


Figure 7.2-1. Air-to-Ground Mission, Nominal Flight Route

configurations while minimizing own exposure to these threats. Two types of BVR air-to-air encounters were simulated. In one, ownship helped prepare for a following blue raid by engaging a red CAP. The other BVR mission type had ownship working in defense against an incoming red raid. There were eight different air-to-air missions, four offensive and four defensive. Two each were used for practice and two each for test.

7.3 Schedule

The complexity of the aircraft being simulated, the novelty of the formats being evaluated, and the amount of data to be collected together yielded four full days on site. Each day began at 0800 and lasted until about 1630. Table 7.3-1 is an

Table 7.3-1. Pilot Schedule Example

Day 1
Ground School SWAT Scale Development Cockpit Familiarization General Flight and Procedures Training
Day 2
Air-to-Air (BVR) Mission Briefing BVR Standard Format Practice BVR Standard Format Test BVR 3D Format Practice
Day 3
BVR 3D Format Practice (continued) BVR 3D Format Test BVR Questionnaire Air-to-Ground (A/G) Mission Briefing A/G Standard Format Practice
Day 4
A/G Standard Format Test A/G 3D Format Practice A/G 3D Format Test A/G Questionnaire Pilot's Oral Critique

example schedule. Pilots participated two at a time, alternating flights. The order of conditions changed from pilot to pilot.

The first day included ground school, Subjective Workload Assessment Technique (SWAT) scale development, cockpit familiarization, and general flight training. Building on the material in the Pilots' Handbook, formats and the interactions among them were introduced in ground school. The static (color viewfoil) examples detailed the specific information available in terms of the symbology, the color coding, and behavior of the individual formats. This early phase of ground school also gave the instructor the opportunity to describe where stereopsis would be introduced into the formats in the 3-D display condition. As the briefing progressed, the availability of alternate formats for a given display, the options and procedures for tailoring a format to pilot preference and phases of flight, the dynamics between displays, and the tasks required inflight were discussed.

A brief period of familiarization in the simulated cockpit provided the pilot with the opportunity to manipulate the displays and explore the format options learned in ground school. The pilots also became acquainted with the simulated aircraft's handling qualities.

During the second, third, and fourth days, pilots were briefed, practiced, tested, and debriefed on the air-to-ground and air-to-air missions. Both mission types were flown in 2-D and 3-D conditions.

7.4 Experimental Design and Data Collection

The independent variables in the main test were: 16 subjects; two conditions, 2-D and 3-D; and two mission types, air-to-ground (4 missions) and air-to-air (2 offensive and 2 defensive missions). Two pilots flew on each of eight weeks.

Alternating flights, the pilots each flew four practice flights under a particular condition, then flew the two test missions shown in the Figure. The pair then moved on to the next condition, repeating the pattern. The schedule was counterbalanced as shown.

Three types of data were collected during and after the test missions to assess the usability and acceptability of pictorial formats and the utility of the 3-D treatment. These data also helped improve both the content and depiction of aircraft, flight, and mission information. The three data types were performance data, questionnaire or opinion data, and subjective workload assessment.

As the pilots flew the missions, a number of performance measures were taken. These were selected to characterize performance in four domains: a) flight path control, b) threat detection and avoidance, c) offensive mission performance, and d) identification and resolution of degraded systems (in air-to-ground missions). The hypothesis was that added stereopsis would improve performance by making the displayed information more readily interpretable. In the analysis, simple descriptive statistics were taken on each of the performance measures and subsets of them were selected for inclusion in multivariate analyses of variance. Since the performance measures differed somewhat between the two mission types - air-to-air, and air-to-ground - they are discussed separately in the following sub-paragraphs.

7.4.1 Air-to-Air Mission Performance

The pilots were instructed to fly the pathway as closely as possible during the ingress and egress segments of the air-to-air missions. Flight path control measures were taken in those two segments. They were:

Percent of the time the aircraft was in the 300 foot wide by 150 foot high pathway entry gate, lateral, vertical and in both axes and,

Lateral and vertical root mean square error from the center of the entry gate.

Threat detection and avoidance were tested with several measures:

Threat exposure score. For each mission, times were accumulated that the pilot spent in each of six conditions of threat exposure. The conditions ranged from being in a threat's potential area of radar coverage to having a missile fired at him at no-escape range. These times were weighted by severity of the threat condition and the weighted times were summed, yielding the threat exposure score.

Track reports. The pilots were instructed to report whenever ownship was tracked by an adversary. The percent reported, the percent correct and the mean response time of the correct reports were recorded.

Countermeasures delivery. Whenever an adversary fired a missile at ownship, the pilots were instructed to release countermeasures, chaff or flares as appropriate. The percent released, percent correct and mean response time of the correct releases were recorded.

Red weapon delivery. It was possible to fly these missions, deliver ownship missiles and withdraw without being fired upon. However this rarely happened, so red missile firings and red missile hits were recorded.

The offensive task assigned the pilots in air-to-air missions was to release the four LONG AIMs and score four hits with them.

The offensive performance measures were:

Number of missiles released and number of hits.

7.4.2 Air-to-Ground Mission Performance

The only flight path control measure taken in the air-to-ground missions was the total time in seconds that the pilot had ownship either under the ground plane or in a mountain. With the amount of practice allowed before the test missions, this was rare and instances were usually short, but some did occur. To preserve the mission, these ground strikes were not fatal.

Threat detection and avoidance were measured several ways:

Threat exposure score. As in the air-to-air case, this measure was a sum of weighted times. The weights were based on threat severity from being in the amber zone of an inactive threat to drawing anti-aircraft artillery fire at close range.

Track reports. The pilots were instructed to report whenever ownship was tracked by a SAM or AAA. The percent reported, the percent correct and the mean response time of the correct reports were recorded.

Countermeasures delivery. Whenever a SAM or AAA launched or fired at ownship, the pilots were instructed to release countermeasures, chaff or flares as appropriate. The percent released, percent correct and mean response time of the correct releases were recorded.

The offensive task in air-to-ground missions was to deliver powered, guided bombs on a target. Targeting latency, delivery latency and delivery offset error were measured.

In each of these missions, the pilots encountered at least one malfunction. The task was to press the master caution light, call up the correct system status format, and report the nature and mission effect of the problem. The mean times to press the master caution, call up the status display and report the problem were recorded as was the percentage of correct reports.

7.4.3 Questionnaire Data

After each set of missions, pilots responded to a questionnaire on the particular formats that supported specific events during that set. Then after the last mission, each pilot was provided with a tape recorder, paper, and a list of general questions. It had been found in earlier studies in this series that the tape recorder technique worked well to elicit ideas not otherwise available - a directed free association. Experience has also shown that aircrew opinion, collected in this manner and collated, is extremely valuable in the assessment and improvement of display formats.

7.4.4 Subjective Workload Assessment Technique

One important goal in the design of these formats has been to reduce, or at least contain, aircrew workload. The Air Force has had some success over the last several years measuring aircrew workload with a program called the Subjective Workload Assessment Technique (SWAT) (Reid, 1985). SWAT was used to characterize workload in the last contract in this series with interesting results (Way, et al, 1987). During the course of the current study, pilots were be asked to quantify the mental workload required to complete their mission tasks. Mental workload refers to how hard the pilot works to accomplish some task, group of tasks, or an entire job. The workload at any one time is assumed to consist of a combination of various dimensions which contribute to the subjective impression of workload. SWAT defines these dimensions as (1) time load, (2) mental effort load, and (3) psychological stress load.

8.0 RESULTS OF THE MAIN STUDY

The results of the main simulation study are presented in this section. They are organized into performance data from the air-to-air and air-to-ground missions, followed by a compilation of the questionnaire responses and SWAT workload information. In Section 9, these results are combined with results from the status format test (Section 6) and open ended questions to provide recommendations and conclusions.

8.1 Air-to-Air Mission Performance

Table 8.1-1 shows the mean, standard deviation and range for each of the air-to-air performance measures under the 2-D and 3-D conditions. The measures are defined in paragraph 7.4.1. Pilot performance was better in the 3-D condition than the 2-D condition on 15 of the 21 measures. Univariate analyses of variance on these measures indicated that the difference between 2-D and 3-D was only significant for the "Red missiles released" variable ($p = .0304$).

Table 8.1-2 is a correlation matrix among these variables. Based on the correlations, the descriptive statistics and knowledge of the variables, three were selected for inclusion in the multivariate analyses of variance. These were:

<u>Ingress RMS Lateral</u> - This was selected to represent the flight path control variables because it is more precise than the percentages, is not influenced by the ceiling effect, and has relatively high intercorrelations with the other variables in this group.

<u>Threat Exposure Score</u> - Since this is a composite measure of threat avoidance behavior, threat exposure score was selected to represent this variable class. It correlated significantly with the track report variables and with response time for correct countermeasures delivery.

Table 8.1-1. Air-to-Air Performance Data

Measure	Condition	Mean	Standard Deviation	Range
Ingress – % lateral	2-D	97.53	9.08	53 – 100
	3-D	99.09	2.82	86 – 100
Ingress – % vertical	2-D	98.97	3.69	79 – 100
	3-D	98.19	5.48	70 – 100
Ingress – % both	2-D	97.03	9.44	52 – 100
	3-D	97.28	6.12	70 – 100
Ingress RMS lateral	2-D	60.19	71.09	23 – 421
	3-D	45.88	20.04	17 – 106
Ingress RMS vertical	2-D	31.63	84.70	2 – 494
	3-D	18.84	12.65	0 – 60
Egress – % lateral	2-D	91.50	10.44	58 – 100
	3-D	91.00	13.88	31 – 100
Egress – % vertical	2-D	79.13	26.45	4 – 100
	3-D	84.00	17.82	20 – 100
Egress – % both	2-D	76.28	27.96	4 – 100
	3-D	80.00	21.62	20 – 100
Egress – RMS lateral	2-D	380.84	778.59	29 – 3625
	3-D	297.23	529.53	19 – 2239
Egress RMS vertical	2-D	227.78	459.40	14 – 2396
	3-D	153.45	254.11	13 – 1174
Threat exposure score	2-D	2288.53	1654.03	0 – 5570.4
	3-D	2111.94	1433.88	0 – 4799.6
% Track reported	2-D	75.52	39.42	0 – 100
	3-D	86.46	25.13	25 – 100
% Track correct	2-D	75.52	39.42	0 – 100
	3-D	86.46	25.13	25 – 100
RT track correct	2-D	3.33	7.73	0 – 37.0
	3-D	4.61	5.81	0 – 20.0
% CM delivered	2-D	94.25	20.16	0 – 100
	3-D	95.83	13.38	50 – 100
% CM correct	2-D	93.75	21.06	0 – 100
	3-D	95.83	13.38	50 – 100
RT CM correct	2-D	2.49	3.12	0 – 8.25
	3-D	4.72	6.31	0 – 26.30
Red missiles released	2-D	0.81	1.06	0 – 3
	3-D	1.56	1.72	0 – 6
Red missile hits	2-D	0.03	0.17	0 – 1
	3-D	0.09	0.30	0 – 1
Own missiles released	2-D	3.97	0.17	3 – 4
	3-D	4.00	0.00	4 – 4
Own missile hits	2-D	3.59	1.04	0 – 4
	3-D	3.84	0.62	1 – 4

Table 8.1-2. Air-to-Air Correlation Matrix

1. Ingress—% lateral	1.000																				
2. Ingress—% vertical	.193	1.000																			
3. Ingress—%both	.866	.609	1.000																		
4. Ingress—RMS lateral	-.647	-.536	-.627	1.000																	
5. Ingress—RMS vertical	-.404	-.626	-.447	.904	1.000																
6. Egress—% lateral	.338	.232	.390	-.267	-.201	1.000															
7. Egress—%vertical	-.043	-.010	-.036	.005	.041	.237	1.000														
8. Egress—% both	.054	.034	.068	-.056	.004	.498	.952	1.000													
9. Egress—RMS lateral	-.322	-.144	-.328	.214	.615	-.689	-.085	-.245	1.000												
10. Egress—RMS vertical	-.169	-.140	-.159	.220	.253	-.378	-.075	-.153	.527	1.000											
11. Threat exposure score	-.119	-.153	-.182	.114	.069	.100	.041	.057	-.247	-.089	1.000										
12. % track reported	.188	-.097	.128	.016	.074	.043	.211	.216	.042	.093	-.311	1.000									
13. % track correct	.188	-.097	.128	.016	.074	.043	.211	.216	.042	.093	-.311	1.000	1.000								
14. RT track correct	.085	-.062	-.027	-.046	-.037	-.088	-.146	-.147	-.165	-.104	.552	-.285	-.285	1.000							
15. % CM delivered	.579	-.047	.475	-.115	.026	.189	-.059	.009	-.210	-.036	-.169	.318	.318	-.040	1.000						
16. % CM correct	.558	-.047	.475	-.115	.015	.171	-.068	-.003	-.196	-.028	-.181	.300	.300	-.030	.994	1.000					
17. RT CM correct	.014	.049	.013	-.060	-.083	-.010	-.077	-.081	-.084	-.151	.325	-.355	-.355	.234	-.221	-.217	1.000				
18. Red missiles released	.054	-.053	-.015	-.095	-.067	.156	.197	.212	-.185	-.176	.482	-.368	-.368	.317	-.143	-.157	.533	1.000			
19. Red missile hits	-.390	.038	-.318	.028	-.012	-.122	.015	-.028	.151	.030	.107	-.210	-.210	.055	-.817	-.788	.264	.144	1.000		
20. Own missiles released	.032	.039	-.046	.044	.011	-.018	-.008	-.020	.003	-.261	.278	-.073	-.073	-.045	-.037	-.378	.005	-.070	.033	1.000	
21. Own missile hits	.084	.006	-.021	.024	.013	.157	.089	.121	.089	-.052	-.464	-.005	-.005	-.553	-.097	-.098	-.060	.105	.084	.400	1.000
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Own Missile Hits - Even though there is a skewed distribution on this variable, it was selected because it best represents ownship's offensive task performance.

Table 8.1-3 summarizes the one-factor, repeated-measures MANOVAS on these three variables representing pilot performance in the air-to-air missions. The first analysis tested for a 2-D vs. 3-D effect. This was not significant. The second analysis tested for the difference between the two sorts of air-to-air scenarios. This difference was significant, but since it was counterbalanced over the other independent variables, could not be said to effect the 2-D vs. 3-D result.

Table 8.1-3. Air-to-Air MANOVAS with Three Selected Measures

MANOVA test for 2-D vs. 3-D
Multivariate tests for significance
Hypothesis df = 3; Error df = 44

Test name	Value	F	Significance of F
Wilkes	0.9244	1.2003	0.3208
Pillai	0.0756	1.2003	0.3208
Hotelling-Lawley	0.0818	1.2003	0.3208
Roy	0.0818	1.2003	0.3208

MANOVA test for Offensive vs. Defensive Scenarios
Multivariate tests for significance
Hypothesis df = 3; Error df = 44

Test name	Value	F	Significance of F
Wilkes	0.7971	3.7322	0.0179
Pillai	0.2029	3.7322	0.0179
Hotelling-Lawley	0.2545	3.7322	0.0179
Roy	0.2545	3.7322	0.0179

In an effort to see if there was an informative pattern in the correlation data, twelve of the original air-to-air measures were selected and a factor analysis was undertaken. The factor loadings reported in Table 8.1-4 are based on orthogonal factors and the varimax rotation method.

Table 8.1-4. Loadings for Twelve Air-to-Air Measures on Three Factors

Measure	Factor 1	Factor 2	Factor 3
Ingress RMS lateral	0.933	-0.084	0.001
Ingress RMS vertical	0.862	0.084	0.035
Ingress – % vertical	-0.671	-0.085	-0.014
Ingress – % both	-0.722	0.481	0.112
% CM delivered	-0.037	0.956	0.225
% CM correct	-0.036	0.927	0.218
Ingress – % lateral	-0.587	0.604	0.118
Own missile hits	-0.027	-0.120	0.084
% Track reported	0.050	0.127	0.946
% Track correct	0.050	0.127	0.946
Threat exposure score	0.141	-0.029	-0.436
Red missiles released	-0.051	-0.021	-0.449

A second set of MANOVAS was conducted on the three factors identified in the factor analysis. They are summarized in Table 8.1-5. As with the three original measures, the difference between scenario types was significant, but that between 2-D and 3-D was not.

Table 8.1-5. Air-to-Air MANOVAS with Three Factors

MANOVA test for 2-D vs. 3-D
Multivariate tests for significance
Hypothesis df = 3; Error df = 44

Test name	Value	F	Significance of F
Wilkes	0.9607	0.6003	0.6183
Pillai	0.0393	0.6003	0.6183
Hotelling-Lawley	0.0409	0.6003	0.6183
Roy	0.0409	0.6003	0.6183

MANOVA test for Offensive vs. Defensive Scenarios
Multivariate tests for significance
Hypothesis df = 3; Error df = 44

Test name	Value	F	Significance of F
Wilkes	0.8240	3.1318	0.0350
Pillai	0.1760	3.1318	0.0350
Hotelling-Lawley	0.2135	3.1318	0.0350
Roy	0.2135	3.1318	0.0350

8.2 Air-to-Ground Mission Performance

Table 8.2-1 shows the mean, standard deviation and range for each of the air-to-ground performance measures under the 2-D and 3-D conditions. The variables are defined in paragraph 7.4.2. Pilot performance was better on the 3-D condition than the 2-D condition on 10 of the 15 measures. Univariate analyses of variance on these measures indicated that the difference between 2-D and 3-D was not significant for any of the variables alone.

Table 8.2-1. Air-to-Ground Performance Data

Measure	Condition	Mean	Standard deviation	Range
Time under ground	2-D	3.05	7.83	0 – 37
	3-D	5.16	8.15	0 – 25
Threat exposure score	2-D	354.44	159.05	141.8 – 828.0
	3-D	366.21	136.56	140.2 – 642.7
% Track reported	2-D	94.10	13.15	50 – 100
	3-D	96.51	10.05	50 – 100
% Track correct	2-D	94.45	13.16	50 – 100
	3-D	96.51	10.04	50 – 100
RT track correct	2-D	3.61	3.65	1.56 – 17.33
	3-D	3.02	1.71	1.16 – 9.08
% CM delivered	2-D	91.16	23.19	0 – 100
	3-D	96.88	12.30	50 – 100
% CM correct	2-D	91.16	23.19	0 – 100
	3-D	95.84	13.36	50 – 100
RT CM correct	2-D	3.98	1.95	0.0 – 7.98
	3-D	3.82	1.29	0.0 – 6.50
Targeting latency	2-D	49.39	58.84	12.8 – 313.0
	3-D	51.85	54.63	14.6 – 207.0
Delivery latency	2-D	1.29	1.03	0.50 – 6.40
	3-D	1.29	1.10	0.60 – 6.40
Delivery offset error	2-D	1668.50	1210.30	562.0 – 5371.7
	3-D	1570.19	1118.65	570.0 – 6409.3
Master caution time	2-D	6.67	9.86	1.30 – 47.30
	3-D	5.68	11.15	1.50 – 60.50
Format callup time	2-D	10.10	9.21	3.50 – 47.30
	3-D	8.51	11.28	2.70 – 62.70
Malfunction report time	2-D	17.48	9.31	9.30 – 48.30
	3-D	15.24	13.27	6.00 – 76.30
% Correct reports	2-D	98.44	8.84	50 – 100
	3-D	95.31	14.81	50 – 100

Table 8.2-2 is a correlation matrix among these variables. Based on the correlations, the descriptive statistics and knowledge of the variables, four were selected for inclusion in the multivariate analysis of variance. These were:

Time Under Ground - This was selected because it was the only measure of flight path control in the air-to-ground missions.

Threat Exposure Score - Since this is a composite measure of threat avoidance behavior, threat exposure score was selected to represent this variable class in air-to-ground as well as air-to-air.

Delivery Offset Error - This variable was selected to represent behavior in the offensive task.

Malfunction Report Time - Since almost all of the malfunction reports were correct, and since this was the last of the cumulative durations measured with the malfunction reports, this variable was selected for the multivariate analysis.

Table 8.2-3 summarizes the one-factor, repeated-measures MANOVA on these four variables representing pilot performance in the air-to-ground missions. The MANOVA tested for a 2-D vs. 3-D effect. This was not significant.

In an effort to see if there was an informative pattern in the correlation data, thirteen of the original air-to-ground measures were selected and a factor analysis was undertaken. The factor loadings reported in Table 8.2-4 are based on orthogonal factors and the varimax rotation method.

A second MANOVA was conducted on the four factors identified in the factor analysis. It is summarized in Table 8.2-5. As with

Table 8.2-2. Air-to-Ground Correlation Matrix

1. Time under ground	1.000														
2. Threat exposure score	.289	1.000													
3. % track reported	-.053	-.279	1.000												
4. % track correct	-.061	-.282	.993	1.000											
5. RT track correct	-.025	.027	-.031	.399	1.000										
6. % CM delivered	-.131	-.080	.232	.237	.077	1.000									
7. % CM correct	-.124	-.087	.218	.223	.091	.976	1.000								
8. RT CM correct	-.102	.113	.146	.182	.317	-.083	-.099	1.000							
9. Targeting latency	.527	.270	.039	.032	.056	-.153	-.177	.034	1.000						
10. Delivery latency	.149	.145	-.062	-.068	.208	-.067	-.051	.091	.278	1.000					
11. Delivery offset error	.036	.175	-.044	-.054	.221	.042	.042	.222	.151	.757	1.000				
12. Master cartier time	.237	.201	-.335	-.341	.013	.039	.042	.140	.304	.289	.208	1.000			
13. Format callup time	.232	.198	-.364	-.364	.067	-.016	-.016	.139	.288	.320	.226	.977	1.000		
14. Malfunction report time	.244	.274	-.351	-.351	.087	.023	.035	.124	.311	.316	.210	.912	.936	1.000	
15. % Correct Reports	.150	-.165	.174	.178	.023	.091	.083	.016	-.118	-.107	.013	-.358	-.333	-.445	1.000
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Table 8.2-3. Air-to-Ground MANOVA with Four Selected Measures

MANOVA test for 2-D vs. 3-D
Multivariate tests for significance
Hypothesis df = 4; Error df = 44

Test name	Value	F	Significance of F
Wilkes	0.9416	0.6826	0.6078
Pillai	0.0584	0.6826	0.6078
Hotelling-Lawley	0.0620	0.6826	0.6078
Roy	0.0620	0.6826	0.6078

Table 8.2-4. Loadings for Thirteen Air-to-Ground Measures on Four Factors

Measure	Factor 1	Factor 2	Factor 3	Factor 4
Master caution time	0.932	-0.222	0.111	0.081
Format callup time	0.915	-0.253	0.068	0.113
Malfunction report time	0.893	-0.244	0.097	0.123
Targeting latency	0.433	0.156	-0.248	0.176
Time under ground	0.371	0.062	-0.201	0.061
Threat exposure score	0.240	-0.195	-0.112	0.145
% Track reported	-0.148	0.981	0.103	-0.008
% Track correct	-0.157	0.966	0.113	-0.003
% CM correct	-0.028	0.127	0.967	0.075
% CM delivered	-0.026	0.144	0.944	0.064
Delivery offset error	0.109	-0.042	0.003	0.862
Delivery latency	0.243	-0.010	-0.110	0.837
RT track correct	0.021	0.000	0.071	0.254

Table 8.2-5. Air-to-Ground MANOVA with Four Factors

MANOVA test for 2-D vs. 3-D
Multivariate tests for significance
Hypothesis df = 4; Error df = 44

Test name	Value	F	Significance of F
Wilkes	0.9712	0.3256	0.8593
Pillai	0.0288	0.3256	0.8593
Hotelling-Lawley	0.0296	0.3256	0.8593
Roy	0.0296	0.3256	0.8593

the four original measures, the difference between 2-D and 3-D was not significant.

8.3 Questionnaire Results

Appendix A summarizes the pilot's general comments and those comments which specifically referred to the information content of the formats. Average ratings for each format are shown as profiles in Figure 8.3-1. Responses along each of the labelled,

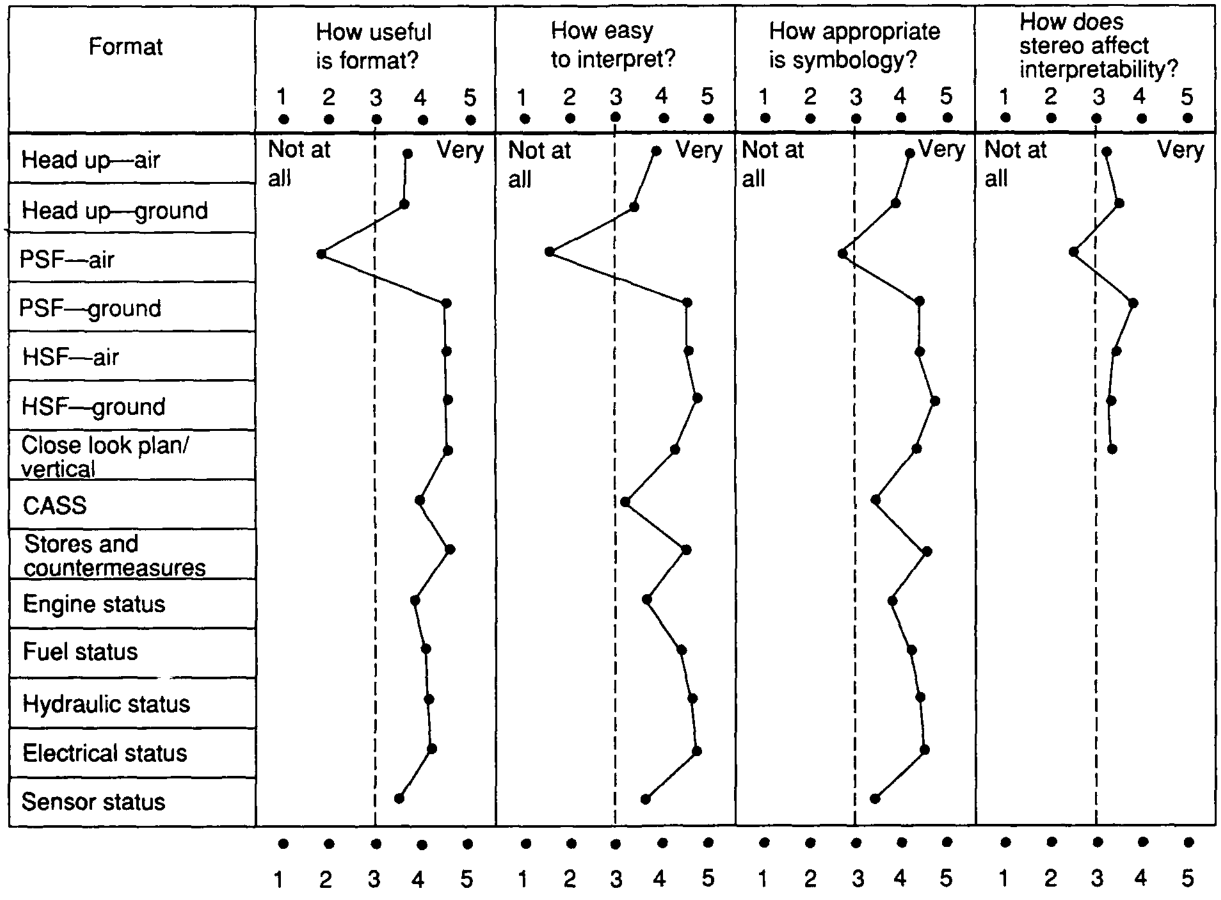


Figure 8.3-1. Mean Opinion Rating for Each Format

unnumbered scales were converted to ratings of 1 to 5, where 1 was the least favorable rating (e.g., "not at all useful"), and were then averaged. With a few exceptions, the ratings obtained from the operational crews were closely grouped and favorable. Results for each of the rating questions are discussed in the following paragraphs.

8.3.1 Usefulness

The HSF both air and ground mode, PSF ground mode, CLF and the Stores and Countermeasures format all received similar highly favorable results. All of these formats received average ratings of above 4.5. Only 4 of the 14 formats received scores of less than 4.0 for usefulness. These formats were the HUD in both air and ground mode, Sensor Coverage and PSF in air mode. Of these, only the latter received a score below 3.0 ("somewhat useful"). Review of the comments made on this format suggest that the reasons for its low usefulness rating were that the grid lines caused the display to be too cluttered. Some evaluators felt modifications were needed to depict a clearer representation of ownship and enemy aircraft altitudes.

8.3.2 Ease of Interpretation

Ratings of interpretability were similar to the ratings for usefulness. Again, the HSF in both ground and air, PSF in ground mode, Stores and Countermeasures Status and the CLF were all very well received. As in the usefulness ratings, only the PSF in air mode was rated less than 3.0 ("somewhat easy to interpret"). As before, comments suggest that the display is just too cluttered.

8.3.3 Appropriateness of Symbology

Rating for symbology appropriateness, with a couple of exceptions, were very similar to ratings on the other categories. Nine of the 14 formats received average ratings of higher than 4.0. The only formats receiving scores less than this were the HUD in ground mode, Engine Status, Sensor Coverage, CASS and PSF in air mode. Only the latter was rated below a 3.0 ("somewhat appropriate"). Again the comments were directed to the issue of clutter due to the range and azimuth grid lines.

8.3.4 Use of Stereo and Interpretability

This option was only available on 7 of the 14 formats. These were the HUD in air and ground mode, the PSF in air and ground mode, the HSF in air and ground mode, and the CLF. Stereopsis was not very well received. While only the PSF in air mode received a score of less than 3.0 ("has no effect"), none of the formats received a score of higher than 4.0. The main concern of the evaluators in this regard was that the use of stereo resulted in lost resolution.

8.3.5 Format Comparisons

In an overall comparison, the HSF in ground mode was the best received. This format received the highest average ratings for usefulness, interpretability and appropriateness of symbology. This was followed closely by the Stores and Countermeasures Format and the HSF in air mode.

All other formats were received fairly well with the exception of the PSF in air mode. Reasons evaluators gave related to an over abundance of grid lines which tended to clutter the display.

Another trend which was expected was that the use of stereo was perceived to be slightly easier to interpret in ground mode rather than air mode.

8.3.6 Information to be Added, Deleted or Changed

Evaluators' suggestions about information to be added, deleted or changed in each format as well as additional comments are summarized in Appendix A. In the table, each suggestion or comment is preceded by the number of evaluators who made that response. Some of these suggested changes will be applied in the conclusion section.

8.4 Workload

Workload in this study was measured using the Subjective Workload Assessment Technique (SWAT). For the pilots, this was a two stage process. First they individually sorted decks of 27 cards bearing all combinations of the definitions of the three levels of the three subscales (time, effort and stress). The card sorts yielded self-calibrations in which each pilot defined for himself how time, effort and stress combined to create workload. A side benefit of the card sort was that it familiarized the pilots with the definitions of the judgements they would be using during the simulated missions.

The SWAT scale was developed from the card sort data. A Kendall's coefficient of concordance was calculated first and found to be 0.7089. This indicated a modest level of agreement among the card sorts for the 16 pilots. Reid, Eggemeier and Nygren (1982) suggested that a more valid scale would be developed by separating the pilots into three prototype groups based on which of the three subscales each indicated in his card sort was the most important contributor to overall workload. When this was done here, five pilots were placed in the time prototype group, five in the effort prototype group and six in the stress prototype group. Subsequent conjoint analyses developed SWAT scales for each of these groups. The mathematical properties of the SWAT scales allowed means across groups to be used in subsequent analyses.

The second stage of SWAT for the pilots occurred during the simulated missions. As each pilot flew the missions, he would hear a tone in his headset every 75 seconds and was instructed to report his workload at that time and for the preceding 20 seconds. SWAT reports were in the form of three numbers, e.g., "3,1,2" which characterized the amount of time, mental effort and stress, respectively, that the pilot was experiencing. The scales developed as above were applied to the judgements and the scaled data means are reported here.

Table 8.4-1 shows the mean SWAT scale values separated by the

Table 8.4-1. Mean Scaled SWAT Reports

Mission type	Display condition	Busy	Not busy	Across BNB
A/A	2-D	17.13	5.45	11.29
	3-D	19.13	5.77	12.45
	Across display	18.13	5.61	11.87
A/G	2-D	33.91	18.13	26.02
	3-D	35.17	18.40	26.79
	Across display	34.54	18.27	26.40

primary independent variables in the study.
these were:

Mission type -	Air-to-air or air-to-ground
Display condition -	2-D or 3-D
Activity -	Busy or not busy. This was an independent judgement, made by an analyst, of the degree of activity at the time of each SWAT report. The 12 SWAT report occasions in each mission were broken into 6 busy and 6 not-busy.
Order -	From the counterbalancing scheme, half of the pilots experienced 3-D first and half 2-D. The order variable reflected that sequence.

An analysis of variance (Table 8.4-2) was performed on the SWAT data set. It indicated that the pilot, mission type and activity variables occasioned significant differences, but that the others did not.

Table 8.4-2. SWAT Analysis of Variance

Source	DF	SS	MS	F	Pr > F
Pilot	15	14232.19	948.81	14.67	0.0001
Mission	1	13520.12	13520.12	209.11	0.0001
Display	1	59.56	59.56	0.92	0.3381
Order	1	1.79	1.79	0.03	0.8679
Activity	1	13264.08	13264.08	205.15	0.0001
Error	236	15258.62	64.66		
Total	255	56336.37			

9.0 CONCLUSIONS AND FORMAT REVISIONS

The first objective of this program was to determine if there is a measurable or perceived advantage in the addition of stereopsis, or a 3-D effect, to the displays intended for use in advanced fighters. The second was to take the pictorial formats through one more stage of development. The conclusions in this section address those objectives.

9.1 Stereopsis in Pictorial Formats

The status format test (Section 6) demonstrated beneficial effects of stereopsis when it was used to augment monocular depth cues. Both response time and error rate were reduced when stereo was added to the sensor coverage format. However, when stereo was used in an attempt to make one format element in a two-dimensional array more conspicuous, it was found to be much less effective than a color change. It was concluded that adding stereo enhances performance by augmenting monocular depth cues, but that it is not an effective replacement for differential color as an attention-getting dimension. The benefit of adding stereo as an additional depth cue has also been demonstrated by Zenyuh, et al. (1988) using a visual search task.

In the main study, the application of stereo had small and mixed effects on performance. The pilots all saw stereo, but questioned its utility, particularly with regard to the resolution penalty in this implementation. An underlying comment relative to the method chosen to produce the 3-D formats with its attendant loss of resolution was that the information transfer was degraded. Numerical information such as airspeed, heading and altitude, and some of the target and switch designators were hard to read at times and slowed the pilot control and response actions because of the increased time required to interpret the information presented.

The flat or negative results and the pilot comments may be partially attributed to the interlaced video which, in conjunction with the stereo implementation, reduced effective resolution. The lesson here is to start with the highest available resolution and try to minimize resolution loss in the stereo implementation. At least in laboratory or simulation environments, ambient illumination can be controlled to reduce or eliminate flicker. This has been demonstrated by Yeh and Silverstein (1989, a and b).

Another factor to be considered is that the amount of disparity added to these formats was deliberately constrained to avoid headache or possible visual anomalies associated with too much disparity. Somewhat bolder use of disparity might have occasioned more noticeable performance differences.

9.2 Suggested Format Revisions

The color pictorial display formats used for these tests were developed from those recommended by Way, et al. (1987). Some of the format changes and adjustments recommended by the aircrew test subjects during that program were incorporated in this 3-D series of air-to-air and air-to-ground display formats.

The second objective was to analyze these pilot comments from the simulation together with the performance data and to recommend further revisions to the formats, where appropriate. Many suggestions for improvement of the formats, and utilization of the 3-D technique were made in the post flight debriefing of the pilots. These are selectively included in the following discussions of individual cockpit displays. Suggestions are made here for revisions to the HUD, the PSF, the HSF, and the CASS format.

9.2.1 Head Up Display (HUD)

In both air-to-air and air-to-ground, the HUD format appeared to be satisfactory. Many of the pilot comments dealt with when to use the pathway and when to use the pitch ladder. The pathway, which is a very compelling format feature, should be reserved for those segments of the mission where precision is required. Examples might include approach to delivery points for some weapons, approach to rendezvous, approach to landing, or close waypoint navigation.

During the engagement and when navigating independently away from a prescribed track, the pilot uses the pitch ladder HUD format illustrated in Figure 9.2-1 which incorporates some

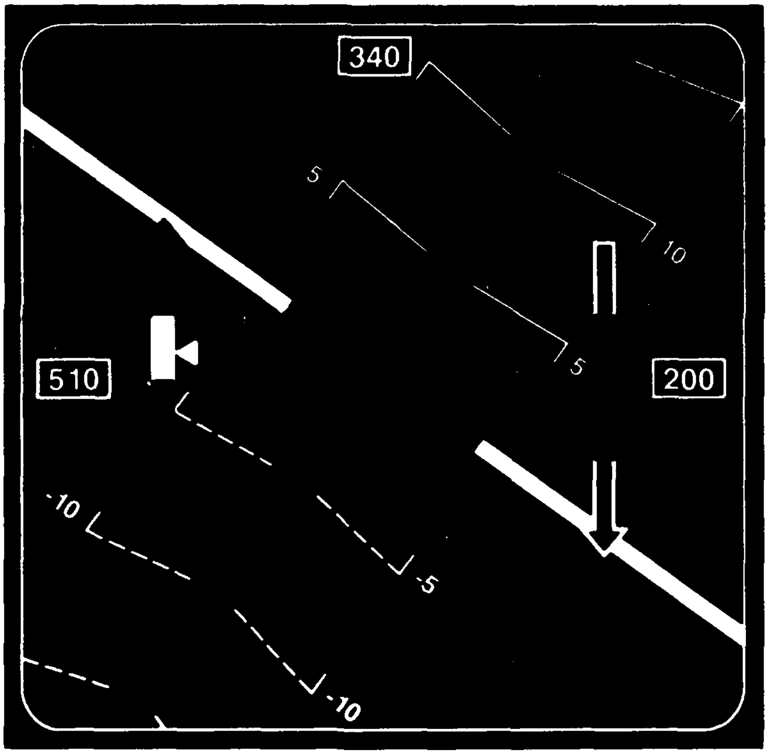


Figure 9.2-1. Recommended HUD Pitch Ladder Format

unique features. The conventional horizontal parallel pitch ladder reference has been changed to 'VEE' the pitch ladder elements toward the horizon. The farther away from the horizon, the more acute the VEE. This will assist spatial orientation and assist in recovery from unusual altitudes. Because of the increasing use of Mach as an airspeed reference, the pilot may select an integrated Mach number in the box versus Calibrated Airspeed.

An alternative pathway mechanization, which includes a speed cue as well as position cues, has been developed in a series of studies, e.g., Hoover, et al (1983). This concept, known as the Command Flight Path Display, involves generating a phantom aircraft in the HUD to represent flight lead. Lateral and vertical guidance is accomplished in the same manner as when flying formation in visual meteorological conditions, or VMC. Ownship speed is controlled primarily by reference to the position of the lead aircraft. With this concept, stereopsis would be used so that when on target speed, lead aircraft appears at the surface of the HUD. When ownship is slow, lead will appear to be beneath the HUD surface and when fast the lead aircraft will appear above the HUD surface and closer to the viewer. The transparent pathway would appear to recede into the display in the 3-D case.

9.2.2 Perspective Situation Format

The air-to-ground PSF was quite effective and was well liked by the pilots. Their recommended changes could be considered fine-tuning. Some support reduction of scan during those times when head-down operation is appropriate.

One problem frequently encountered was the tendency to fly below the 200 foot briefed terrain clearance plane. A contributor to this was the cursor control which was mounted on the flight control stick. It should be moved to the throttle to preclude cross-coupling from cursor movement to pitch input. Another part of the solution is to add a readout for selectable terrain clearance altitude, and then add a command arrow on the altitude readout which would operate like the one on the HUD (See Figure 9.2-2). The altitude readout, terrain clearance altitude and command arrow would be amber for a caution level annunciation until halfway down to zero altitude, then go red as a warning.

Other recommended changes to the PSF in ground mode are to make the threat shapes transparent, so the mountains beyond them can be seen and to add outline threat shapes to correspond to the outlines for inactive threats on the HSF. The idea of transparency is a good one and its implementation depends on the capabilities of the display generator employed. Outline shapes for inactive threats were used in previous contracts in this series and they were missed by the pilots here. The clear message is that they should be returned, both for the information they carry and to maintain consistency with the HSF.

Another recommendation is to add a flight path predictor to the ownship symbol. This concept, which has been used successfully in other applications, shows the pilot where his current airplane attitude and speed will take him 10, 20 and 30 seconds in the future. It would be in the form of a curved, three segment, ribbon with breaks at 10 and 20 seconds out and ending 30 seconds out. A judicious amount of damping, added to the predictor dynamics, is necessary to smooth its movement.

To avoid a large vertical excursion of the scan up to the HUD to determine aircraft attitude, it is suggested that a pilot selectable attitude indicator insert in a small "window" be available at the bottom of the display. Figure 9.2-2 shows the PSF with all of these suggested modifications added.

An alternative, more compelling, way of showing deviation below selected terrain clearance altitude would be to add a horizontal "curtain" which appears from the bottom of the display as soon as the aircraft descends below the preset altitude. Note that when the clearance altitude is zero, the curtain is all the way up to the horizon.

The perspective situation format in air mode was not successful in providing the hoped-for information transfer. Pilots were reluctant to use it in its present form.

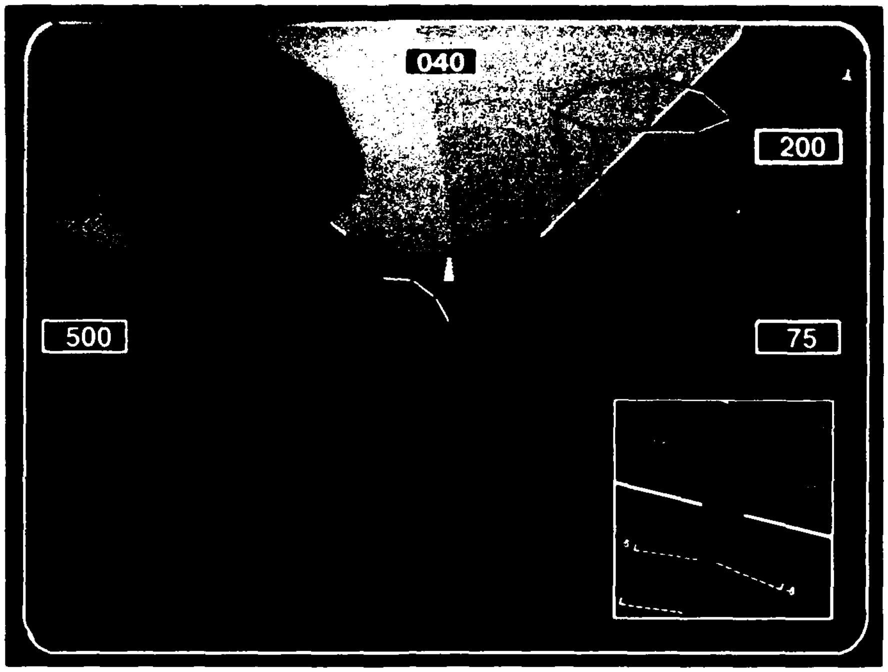


Figure 9.2-2. Recommended Perspective Situation Format, Ground Mode

The pie shaped, forward-looking wedge shown in Figure 9.2-3 may be an improvement on what the pilots saw. It is similar to the format selected and specified for this program, but it failed in the implementation due to difficulty with the Poly-2000 display

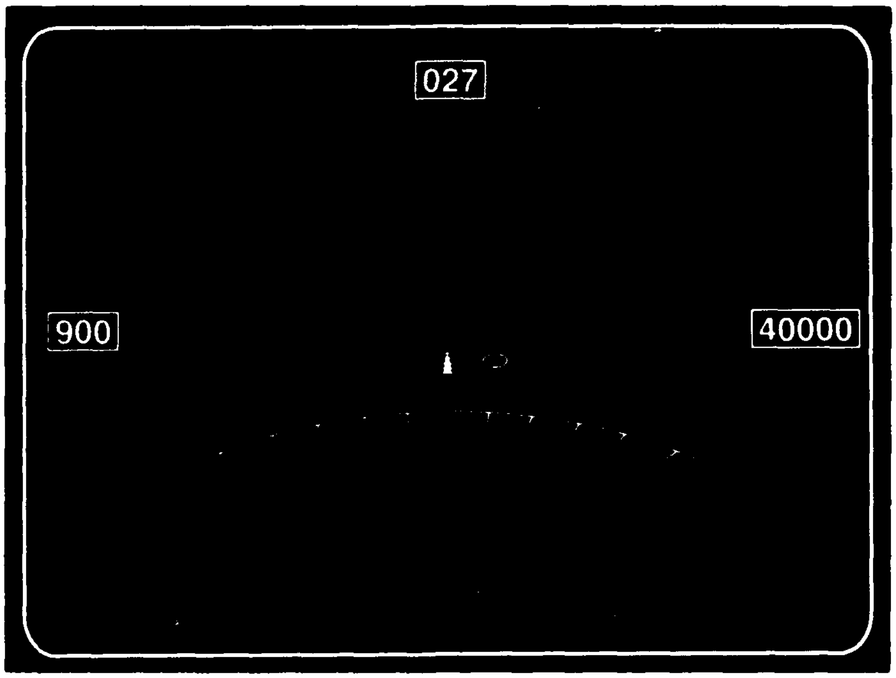


Figure 9.2-3. Recommended Perspective Situation Format, Air Mode

generator. As a result, the concept was not adequately tested. It is recommended that this approach should be retained and further investigated. The one suggested change is to reduce the grid lines to only those necessary to define the volume. Parametric information on air traffic is available on the Close- Look format.

9.2.3 Horizontal Situation Format

The HSF remains essentially unchanged from the initial version used in the simulation, with only minor improvements. The cursor implementation should be somewhat changed. First, as noted above, the cursor control should be moved to the throttle to preclude cross-coupling into aircraft controls when inputs are made for the cursor. Second, it would reduce workload to leave the cursor on the HSF all the time, rather than having to call it up with a separate switch action. The general cursor symbol should start at a home position near the ownship symbol. Once moved, it should stay at its new ground position until moved again or defined (the new location identified as a target, waypoint, or track file input).

The predictive vector suggested for the PSF should be repeated on the HSF. This would indicate the path of the airplane for the next 30 seconds, given the current airplane attitude and speed.

9.2.4 Crew Alerting and Systems Status (CASS)

The symbology for the consequences of various failures should be replaced by a plain English text. It is suggested that when the CASS reports a failure, the appropriate system diagram be automatically selected and displayed on the left MPD. Then remedial actions could be brought up with the diagnostic display in the form of interactive checklists similar those used in the previous program (Way, et al, 1987).

The remainder of the system formats were quite effective and well accepted, with the exception of the sensor coverage format, which was not heavily exercised in these simulations. No further change is recommended to these formats at this stage in their evolution.

REFERENCES

Hoover, G. W., Cronauer, V. T., and Shelly, S. Command Flight Path Display, Phase I and II, Final Technical Report, NADC-85111-60, Naval Air Development Center, Warminster, PA, September 1983.

Jauer, R. A. and Quinn, T. J. Pictorial Formats, Vol. I, Format Development, AFWAL-TR-81-3156, Vol. I. Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, OH, February 1982.

Reid, G. B. Current Status of the Development of the Subjective Workload Assessment Technique. Proceedings of the Human Factors Society 29th Annual Meeting, 220-223, Santa Monica, CA, October 1985.

Reid, G. B., Eggemeier, F. T. and Nygren, T. E. An Individual Differences Approach to SWAT Scale Development. Proceedings of the Human Factors Society 26th Annual Meeting, 639-647, Santa Monica, CA, October 1982.

Tolin, P. Application of Dynamic Stereographic Imagery to Cockpit Displays, Final Report to the Boeing Military Airplane Company, Contract GP0917, January 1986.

Way, T. C., Hornsby, M. E., Gilmour, J. D., Edwards, R. D. and Hobbs, R. E. Pictorial Format Display Evaluation, AFWAL-TR-84-3036, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Laboratory, OH, May 1984.

Way, T. C., Martin, R. L., Gilmour, J. D., Hornsby, M. E. and Edwards, R. E. Multi-Crew Pictorial Format Display Evaluation, AFWAL-TR-87-3047, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, OH, February 1987.

Yeh, Y-Y. and Silverstein, L. D. Using electronic stereoscopic color displays: Limits of fusion and depth discrimination. Proceedings of the Society of Photo-Optical Instrumentation Engineers, 1989 (a).

Yeh, Y-Y. and Silverstein, L. D. Depth Discrimination in Stereoscopic Displays, Society of Information Display Symposium, 1989 (b).

Zenyuh, J. P., Reising, J. M., Walchli, S., and Biers, D. A Comparison of a Stereographic 3-D Display versus a 2-D Display Using an Advanced Air-to-air Format. Proceedings of the Human Factors Society 32nd Annual Meeting, 53-58, Santa Monica, CA, October 1988.

APPENDIX A

DETAILED QUESTIONNAIRE RESPONSES

The format questionnaire is discussed and responses are summarized in Section 8.1. This appendix contains a collation of specific responses to the questions of what information should be added to, deleted from, or changed in presentation on each of the formats. Parenthetical numbers indicate the number of pilots who made the comment.

HEAD-UP DISPLAY - AIR MODE

Information to be added:

(5) Mach number and G. readouts
(2) Display final ALT/AS desired by capture path.
(2) Display vector on track symbol.
(2) No additions necessary.
Ground reference tick marks on pitch ladder.
Need for declutter levels.
Need range readout.
Needs basic altitude reference.
Low altitude warning system with sexy female voice.
Automate countermeasures dispensing.
Autopilot disconnect indicator.
Angle of bank indicator.

Information to be deleted:

(10) No deletions
(3) Needs more information
Delete capture path, couple it in autopilot.
Remove 3-D format.
Remove heading marks along top.
Remove missile/AAA site azimuth vector, it is redundant.

Information to be changed:

(4) Enlarge pitch angle, ALT/AS numbers.
(4) Enlarge captuie pathway.
(2) "Shoot" cue needs to be bolder (different color, flash).
(2) Have track launch arrows point toward aircraft.
(2) Improve VSI indicator.
Reverse MLE arrow to point up with R_{ne} at top and R_1 at bottom.
Color code altitude reading for warning purposes.
More specific altitude commands.
Improve steering symbology.
Have green change to black as it passes through horizon line.

HEAD-UP DISPLAY - GROUND MODE

Information to be added:

(4) Mach number, G, bank indicators
(7) Clearer terrain clearance info.
(4) Alt. warning for dropping below preset altitude.
(2) Time/distance display to next way point, will assist in maintaining time schedule.
Min/max/optimum speed indicator for each segment.
Missile envelope to assist in shot selection.
Indicator to determine when climbing is necessary.
Clock position indicator w/o referring to PSF.
Radar altimeter information.
Barometric altimeter pressure setting.
Altitude reference.
Steering to weapon release box.
Launch range for guided missiles.

Information to be deleted:

(7) Nothing needs deleted
(2) Needs more information
Remove heading tick marks along top.
Remove 5^{o} increment # on pitch ladder, have # every 10^{o}, tick marks every 5^{o}.

Information to be changed:

(2) Numbers need to be larger.
Shoot cue needs to be more evident.
Weapon selection/status display on top of HUD.
Computerized steering to waypoint via capture path.
Vertical speed indicator.
Earlier indication of direction to steer.
More depth needed on pathway.
Better correlation HUD-HSF.
Improve weapon indication.
Improve bank angle indicator readability.
Improve symbol 3-D effect.
Mountains should be brown.
Change sky from black to blue.
Move cockpit ADI for accessability.

PERSPECTIVE SITUATION FORMAT - AIR MODE

Information to be added:

(4) Nothing needs to be added.
High threat SAM belts.
Don't add - change.
Graphic representation of radar coverage window.
Scale up/down.
High threat SAM belts.

Information to be deleted:

(4) Remove entire display.
(3) Remove grid lines.
(2) Nothing needs to be removed.
Remove 3-D format.
Remove tick marks every 10NM.
Bearing lines every 10^{o}.

Information to be changed:

(2) Use rings representing distance ownship as center - use poles to represent altitudes.

(2) Ground grid needs declutter.
Make alt. vector of ownship proportional with enemy's.
Change to side view with ownship & opponent radar coverage along with opponent location data.
Show targets in close-look format.
Target set (A,B or C) should be constant size.
Expand vertical axis.
Enlarge vertical pie wedge, with ownship as center.

Comments:

Never used format; wasn't sure what use it was. It needs help, but I don't know how to fix it. Did not use this display much.

PERSPECTIVE SITUATION FORMAT - GROUND MODE

Information to be added:

(5) Attitude & low alt. reference.
(2) Altitude warning.
(2) Cursor display indicator
    Chaff/flare cue.
    Additional "close up look" scale (5NM).
    Add pathway guide around threats & terrain.
    Enlarge ownship size.
    Flight path marker near horizon.
    Pre-briefed SAM/AAA sites displayed.
    Indicator so pilot knows geographically where weapons are being targeted.
    ETA to next waypoint.

Information to be deleted:

(6) Nothing needs to be removed.
(2) Needs more information; everything looks good.

Information to be changed:

(5) Change threat envelopes so they can be seen through.
    Add declutter switch to SAM/AAA info.
    Combine with terrain clearance info.
    Add texture to ground.
    Improve interpretability of VSI ladder display.
    Improve interpretability of when to make a turn.
    Improve range information.
    Move HDG to different position.
    No changes required.

HORIZONTAL SITUATION FORMAT - AIR MODE

Information to be added:

(5) Nothing additional needed.
(2) Auto ranging feature.
Launch range of ownship.
Digital readout of range to designated groups.
Continuous display of selected group - symbol difficult to read.
Radar vertical coverage at cursor location.
Heading marker indicating egress location.
Green zones for egress.
ADL or flight path vector
Shoot cue on this display.
Target track numbers.

Information to be deleted:

(5) Nothing should be deleted.
(2) Include range arrows on 2 targets to reduce clutter.
Remove range arrow from targets with tail to us.
Only display MLEs in multibogey situation which are most threatening.
Reduce # of range rings

Information to be changed:

(3) Cursor should remain in place without having to be recalled.
(2) No changes necessary.
(2) Difficult to see letter designations on long range threats.
Make inner range rings dashed.
Need to be able to designate out of range aircraft.
Put cyan arrow pointing to INS on compass rose.
Use different symbology for fighters/bombers.
Enlarge target boxes, bolder.
Enlarge compass rose numbers.
Fixed size target indicator group.
Cyan group designator is too faint.
Indicate group (A/B/C) is indicated on close-look format.
Side view showing ownship & energy sensor coverage.
Rubber range step scan switch.
Should change locations with close-look format.

Comments:

(2) O.K.
One of better displays
Good job.
It is great as it is.

HORIZONTAL SITUATIONAL FORMAT - GROUND MODE

Information needed to be added.

(2) Nothing additional needed
(2) ETA clock to next waypoint.
Low Alt. warning indicator.
Turn radius radius indicator.
Velocity vector.
G indicator.
Missile/weapon area of lethality.
Label SAM sites.
Have 15 NM scale.
Show predicted flight path.
Ability to display via datalink - dots blinking along missile track would indicate missile position.

Information to be deleted:

(8) Nothing needs deleted.
Missile track heading pilot knows if missile came off.

Information to be changed:

(2) Cursor should remain superimposed on aircraft until moved.
Display aircraft turn radius at airspeed.
Incorporate G meter.
Launch symbol should flash.
Symbols larger and more distinct.
Compass rose needs more detail.
Change Cursor/background color.
Different means of moving cursor.
Ground mapping more realistic, less cluttered.
Target tracking needs to be more accurate.
Change Scan Step to rubber range.
New switching system for range scale. cursor at top of scope expands scale, bottom decreases scale.
Means of determining whether SAM/AAA threat is "up" or not.
Allow for flying pathway to any designated path have ability to preview a route.

Comments:

Good display, located nicely.
3-D no appreciable effect.
No change required.

CLOSE-LOOK FORMATS (PLAN/VERTICAL VIEWS)

Information to be added:

(4) Constant simultaneous display of target information; (ALT,A/S,Type..).
(2) Aircraft type next to pushtiles.
(2) Nothing additional needed.
MLE.
Alt, Mach # indicator.
Range directly next to blue ownship vector.
Range information between targets.
Closure rate.
ECM Cues.
Ability to see what targets have been selected by other A/C.

Information to be deleted:

(6) Eliminate Vertical View format.
(6) Nothing needs deleted.
Eliminate target destroyed display, display, remove target.
Eliminate blue color.

Information to be changed:

(4) Pilot should control # sequence, prioritize targets.
(2) Need easier way of reselecting primary target.
(2) Different symbols for fighters and bombers.
Need easier way of determining scale limit.
Vertical view needs way of showing altitude.
Range instead of scale up/down.
Color code of targets could be simplified.
Put color coded in target rather than shading in altitude reading.
Multiple data under same key, reduce data search time.
Allow targeting from HSF.
Auto scale.
Decrease size of aircraft in order to track fighters/bombers all the time.
Rubber range via step scan.

Comments:

(2) Really liked display. Overall format is right on track.

CREW ALERTING AND SYSTEM STATUS (CASS) FORMAT

Information to be added:

(2) Nothing additional needed.
(2) Checklist procedure for emergency procedures trouble shooting, emergency action information.
More systems avionics, instruments...
Cabin pressure, 0_2 system, radar RWR, EWWS indicators.
Amber alert on fuel system.
Flames to engine to indicate afterburner.
Best RG/Endurance/Climb/Corner information.

Information to be deleted:

(4) Nothing needs deleted.
Throttle position indicator.
Engine status information. Only need Max AB, MIL, idle.
Eliminate entire display. display.
Doesn't need immediate impact information should know what it is.

Information to be changed:

(7) Do not need the use of separate screens.
(4) Describe the problem in words.
(3) Flight safety information needs to be quicker to understand.
Red color was difficult to see.
Change all colors to blue unless malfunctioning.
Increase fuel total indication size.
Increase Joker/Bingo number size.
Condense Joker/Bingo to low fuel light.
Tie in malfunctioning system with subsystem selection status.
Match symbol on status format with that on CASS.
Left MPD could automatically display sub-system identified by CASS.
All pages should be the same.
Green: normal, Amber: malfunction, Red: major problem

ENGINE STATUS FORMAT

Information to be added:

(3) Nothing additional needed
(2) Nozzle position % open
(2) Numerical values for oil press, Oil quantity, EGT, master arm.
Letters by gauges - defining them.
RPM readout at ladder
Engine related systems indicator: nozzles, bleed air.
Flame on engine to indicate afterburner.
Loss of cabin pressure indicator.
Engine specific fuel components
Audio

Information to be deleted:

(6) Nothing needs deleted.
Remove throttle position indicator.
Remove throttle position indicator.
Remove picture of engine.

Information to be changed:

(3) Have it on only when monitoring is needed.
(3) Change from pictorial gauges to word warnings.
Display EGT & OIL indicators at all times to catch trends.
Oil and Temp symbols were too similar.
Pie pressure graph rather than bar graph.
Label symbols in same way.
Keep engine status colors the same.
Change colors to blue unless malfunctioning.
No changes necessary.

Comments:

Good display.
Good information - difficult to interpret.

FUEL STATUS FORMAT

Information to be added:

(3) Nothing additional needed
(2) Digital readout of lbs of fuel left in each tank.
Expected fuel consumption to reach every point based on current fuel consumption.
Clear representation of Flames to indicate afterburner.
Annunciator light panel for subsystems.
Display all pumps, valves, fuel controls..
Needle gauge might make interpretation easier.
Bingo profile info: airspeed, climb speed, altitude, heading.

Information to be deleted:

(4) Nothing needs to be deleted.
Remove throttle position indicator.
Joker/bingo fuel isn't necessary - low fuel warning might be better.

Information to be changed:

(3) Nothing needs to be changed.
(2) Joker/bingo indicator needs larger.
Transfer or boost pump failure should appear in red.
Afterburner should not be amber, (caution designation).
Larger tank box needed.
Don't need entire plane figure, TDT, LBS circles sufficient.
Right MPD too small.
Left MPD symbols not useful, used only gauges.
Enlarge fuel total indicator.
Standardize colors.
Only use blue unless malfunction exists.
Bad fuel pump symbology not clear.
Need better joker/bingo notification.
Engine, fuel status symbology needs to be different.

Comments:

Does system allow for identification of imbalance.
Good system,can it detect leaks?

HYDRAULIC STATUS FORMAT

Information to be added:

(6) Nothing needs to be added.
(2) Hydraulic filter & pressure status to warn of impending failure.
Checklist of emergency action.
Loss of cabin pressure cue.
Annunciator light panel.
Label different components.
Hydraulic subsystems affected by failure.
Master arm on/off indicator.

Information to be deleted:

(9) Nothing should be deleted.
Remove all blue color.
Remove entire display.

Information to be changed:

(5) No change required.
Display only what has failed.
Instead of lighting affected area, listing them would convey information quicker.
Color code each system lost.

Comments:

System over-simplifies a failure.
Having to go between CASS takes time away from flying.
Symbology of components very clear.
I can always tell right off when there is a failure and what is lost.
Get all displays like this with the same colors and the CASS system will work good.

ELECTRICAL STATUS FORMAT

Information to be added:

(6) Nothing additional needed.
(2) Add effect of failure on subsystems.
Annunciator light panel.
Checklist display.
Master arm on/off indicator.
Popped CBs.

Information to be deleted:

(8) Nothing needs deleted.

Information to be changed:

(5) Nothing needs to be changed.
(2) Standardize colors.
Use all blue except for
Having to go between CASS and status takes away from flying time.

Comments:

Great format.
Display is good.
It is a good clear indicator.
Too bad every display isn't displayed this way.
Quick, easy recognition of failed system.
Didn't get much of a chance to use it.

STORES AND COUNTERMEASURES STATUS FORMAT

Information to be added:

(6) Nothing additional needed.
Pilot should be able to select deployment pattern.
Time to release indicator.
Quantity to release indicator.
Hung ordnance symbology.

Information to be deleted:

(10) Nothing needs to be deleted.
Delete green: annotate when chaff/flare required.
Amber should go away automatically upon dispensed.

Information to be changed:

(4) Chaff/flare dispenser levers should be on throttle.
(3) Nothing should be changed.
(2) Chaff/flares must be dispensable when screen is off.
(2) Better indication of what is available, what is used.
Master arm info should be available when screen is off.
Arms should not be fireable when out of range without first pressing out of range button, reduce # of bad shots.
Need auto and manual modes, rotary switch to select # of bundles.
Better feedback as to what is hot at trigger.
Master arm should be blue when off, red when on.
Halos are too confusing.
Fire command should be placed in front of pilot.

Comments:

Very good display, should be left on MPD.
Keep format, very useful.
It is a clear way of displaying stores.
Good color coding for missile targeting and selection.

SENSOR COVERAGE FORMAT

Information to be added:

Word description of affected system.
Annunciator light when failed.
Master arm on/off indicator.
Information as to what sensor covers which areas.
More info on each subsystem to determine mission impact.
ECM, ITCM, RWR indicators.

Information to be deleted:

(2) Nothing needs deleted.

Information to be changed:

Need degraded coverage info, bearing indicator.

Comments:

(5) Not used for these tests.
Good for displaying battle damage.
Not needed.
Pretty picture.

APPENDIX B

OPEN-ENDED QUESTIONS AND RESPONSES

As the last exercise in opinion data collection, pilots were given a list of open-ended questions and a tape recorder. Previous studies in this series have shown this to be an effective way to elicit ideas not otherwise available. The tapes were transcribed and are summarized here.

1. What is your opinion of the Pathway-in-the-Sky (PITS) on the HUD? Does it provide sufficient information for flight path control during low level flight? During which flight and mission phases is it most useful? Are there any flight or mission phases when it is not useful?

6 Pilots	Could provide some information at low level.
4 Pilots	Manual flight with pathway requires high level of concentration.
3 Pilots	Useful if this degree of flight path precision is really required in manual flight.
2 Pilots	Works well for straight and level flight.
1 Pilot	Liked top - bottom pattern difference.
1 Pilot	Good display.
1 Pilot	Would be useful if navaids were inoperative.

3 Pilots	Not particularly useful in air mode.
1 Pilot	At altitude, could be used to provide vertical path guidance for minimum fuel burn, etc.
1 Pilot	At altitude, HSF provides best horizontal guidance.
1 Pilot	Great for air intercept control.

3 Pilots	Pathway at low level could be useful if it followed a "best path" through terrain and threats.

2 Pilots	Bring entry gate to full screen size.
2 Pilots	Make pathway more responsive to actual aircraft state and terrain following requirements.
1 Pilot	Symbology is too small.
1 Pilot	Add "ghost" wingman to fly formation on.
1 Pilot	Put course arrow on the heading tape.
1 Pilot	Add ground clearance levels.
1 Pilot	Show final altitude in climb or descent, rather than some intermediate level.
1 Pilot	Add centerline.
1 Pilot	Hard to follow entry point.
1 Pilot	Add steering box to command wing position.
1 Pilot	Move vertical velocity to the horizon line.
1 Pilot	Difficult to lead intersections in turns.
1 Pilot	Not accurate to fly below 500 feet, at night or in weather.
1 Pilot	Make entry gate more prominent.
1 Pilot	Needs better attitude reference.

2. What is your opinion of the Missile Launch Envelope (MLE) information presented on the HUD (MLE arrows and carets)? Any suggestions for changes?

10 Pilots	Good idea.
3 Pilots	Extremely useful.
2 Pilots	Like having adversary MLE as well as mine.
1 Pilot	Question ability to determine the precision of information required for MLEs.

How Change?

1 Pilot	Save green until system really recommends a shot, not at maximum range.
1 Pilot	Use darker and lighter green, rather than green and white for in-range and no-escape MLE zones. Use same logic on threat MLE.
1 Pilot	Indicate on caret which threat it's for.

1 Pilot	Add dynamic seeker ranges, if important.

1 Pilot	Invert logic for threat MLE.

1 Pilot	Add steering cue to heart of missile envelope.

1 Pilot	Add escape cue.

1 Pilot	Add prompter for when in range.

1 Pilot	Add indicator for higher priority threat than current target.

3. What is your opinion of the Perspective Situation Format (PSF) in Ground Mode? How well does it provide information about the tactical situation? Any suggestions for changes?

13 Pilots	Very useful; outstanding.

3 Pilots	Threat and terrain depiction good.

2 Pilots	3-D good for threat depiction.

1 Pilot	3-D marginally better than 2-D.

1 Pilot	Like one mile ground squares.

1 Pilot	Requires very precise information not currently available.

How Change?

4 Pilots	Make SAM and AAA envelopes transparent to see terrain beyond.

4 Pilots	Add bank angle and flight path predictor.

3 Pilots	Add ownship altitude information.

2 Pilots	Have pathway take you around threats and terrain here and also on the HUD and HSF.

1 Pilot	Display scale and allow pilot to control it.

1 Pilot	Add targetting and drop point information.

1 Pilot	Pathway and numerics too small.

1 Pilot	Bring viewpoint closer to airplane to reduce close-in wasted space.

1 Pilot	Put cursor and IP marker on the PSF.

1 Pilct	Put correlated cursor on PSF and HSF.

1 Pilot	Add prebriefed threats in outline form like HSF.

1 Pilot	Sometimes too cluttered.

1 Pilot Add caret on horizon for point toward which you are currently heading.

1 Pilot Add turn radius information.

1 Pilot Give PSF same field-of-view as HUD

1 Pilot Add shoot box.

4. What is your opinion of the Perspective Situation Format (PSF) in Air Mode? How well does it provide information about the tactical situation? Any suggestions for changes?

12 Pilots Little or no use.

3 Pilots Poor implementation of possibly good idea.

How Change?

4 Pilots Show dimensioned side view with ownship, aircraft and radar coverage.

2 Pilots Reduce number of grid radials and arcs to reduce clutter, make full screen, increase altitude scale.

1 Pilot Show dimensioned side view with aircraft labeled by model.

1 Pilot Do in 2-D to increase resolution; Label to correspond to HSF/CLF track file designations. Make a given altitude the same height on the display at any range.

1 Pilot Show 360 degree coverage with normal range markings and aircraft on calibrated sticks.

1 Pilot Do in 3-D and increase resolution.

1 Pilot Add radar coverage.

1 Pilot Eliminate 3-D.

1 Pilot Change scale.

5. What is your opinion of the Horizontal Situation Format (HSF) in Ground Mode? How well does it provide information about the tactical situation? Any suggestions for changes?

15 Pilots Very good display.

1 Pilot	Didn't notice any 3-D benefit.
1 Pilot	Good for navigating through terrain.

How Change?

2 Pilots	Add ownship predictive vector.
2 Pilots	Scale control confusing.
2 Pilots	Add ability to center HSF on something other than ownship.
2 Pilots	Show threat model, e.g., SA4.
1 Pilot	Add time-over-target information and speed guidance to meet TOT requirements.
1 Pilot	Label the SAM sites - SA6, etc.
1 Pilot	Eliminate own missile in flight.
1 Pilot	Flash missile launches at ownship.
1 Pilot	Keep cursor in view, eliminate button press.
1 Pilot	Don't cycle scale change. Stop at lowest scale for "Scale Down" and highest for "Scale Up".
1 Pilot	Label "Range Up" and "Range Down" vs. "Scale".
1 Pilot	Control range with rotary switch.
1 Pilot	Use autoscaling
1 Pilot	Add alert for pop-up threat.
1 Pilot	Add attitude and altitude information.
1 Pilot	Show whole MLE, rather than just one cut through it.
1 Pilot	Add indication of when other friendlies shoot displayed threats.
1 Pilot	Distinguish better between briefed threats that just went active and pop-ups that just appeared for the first time. Put this under switch control so a dedicated HARM shooter would have the indication of who's active and the low-level bomber would see them all as threats.
1 Pilot	Add 15 mile scale; eliminate 160 mile scale.
1 Pilot	Compass rose needs more detail.
1 Pilot	Add time to selected points.
1 Pilot	Add shoot cue.

6. What is your opinion of the Horizontal Situation Format (HSF) in Air Mode? How well does it provide information about the tactical situation? Any suggestions for changes?

14 Pilots	Good presentation.
2 Pilots	Do not change it.
1 Pilot	Liked compass rose.
1 Pilot	Used compass rose in air mode, not in ground mode.
1 Pilot	Liked center-decenter feature.
1 Pilot	Liked MLEs.
1 Pilot	Provides mainly navigation and threat information.

How Change?

5 Pilots	Make track file designators more prominent.
3 Pilots	Leave cursor out where I put it, rather than having to start from ownship each time.
2 Pilots	Reduce clutter by only showing MLE's for first two targets I've selected, then step ahead as I shoot.
1 Pilot	Add pilot overridable automatic scale change.
1 Pilot	Add RMax arc around ownship.
1 Pilot	Have adversary MLE indications reflect his aspect, i.e., he cannot shoot me when he's tail on.
1 Pilot	Reduce number of range rings.
1 Pilot	Add egress heading to compass rose.
1 Pilot	Allow designation as soon as groups appear, rather than waiting for radar coverage.
1 Pilot	Put course arrow on the compass rose to indicate the direction to the next waypoint or egress point after the air-to-air engagement.
1 Pilot	Indicate vertical dimensions of radar coverage, somehow.
1 Pilot	Add full time window with cursor bearing and range.
1 Pilot	Declutter MLEs somehow.
1 Pilot	Have more selectable scan patterns.
1 Pilot	Gets cluttered when Red and Blue merge.
1 Pilot	Enlarge compass heading.

1 Pilot Put numbers on compass rose every 30 degrees.

1 Pilot Indicate why Close-Look not available when called up.

1 Pilot Add more ground threat information.

7. How easy is it to correlate threat type, position and mode information across the PSF and HSF? How useful is it to have threat information presented on two displays with different viewpoints?

4 Pilots Fairly easy to use.

3 Pilots Excellent.

3 Pilots Good correlation in ground mode.

2 Pilots In air mode, HSF and better PSF would be good.

1 Pilot Have CLF airplane numbers reflect pilot selected order.

1 Pilot Put track letter designations on PSF as well as HSF.

1 Pilot In air mode, would be easier to have HSF and side view.

1 Pilot Leave HSF unchanged, but combine HUD and PSF information to reduce scan.

1 Pilot Never used PSF in air mode.

1 Pilot Easy to tell threat type.

1 Pilot Good confidence factor to have another viewpoint.

1 Pilot Too many buttons to push for information.

1 Pilot No correlation in air mode.

1 Pilot Need altitude reference.

1 Pilot Move HSF to where Cass is to reduce head-down time.

8. Which display (HUD, PSF, HSF) did you find most useful for threat information? Least useful? Was the distribution of threat information across the HUD, PSF, and HSF appropriate? If not, what would you change about the distribution?

5 Pilots HSF most useful.

3 Pilots Air mode PSF least helpful.

3 Pilots In ground mode I used HSF, then PSF to thread between threats and terrain.

3 Pilots	In air mode, HSF was most important, used with CLF.
2 Pilots	PSF was primary threat avoidance display.
2 Pilots	HUD at first and then HSF or PSF for details.
2 Pilots	Distribution of threat information was good.
2 Pilots	HUD least useful for threat data.
2 Pilots	HUD most useful.
2 Pilots	Make characters larger on HUD, PSF and HSF.
1 Pilot	HSF too cluttered.
1 Pilot	HUD least useful in ground mode because no threat locations were shown and range to terrain not clear.
1 Pilot	In HSF, track and launch information sometimes lost in threat footprint. Colored alert information is more effective on format (like HUD) with less other color.
1 Pilot	HUD would be more important at close-in ranges.
1 Pilot	Close Look was good addition.
1 Pilot	Need prebriefed threats on PSF.
1 Pilot	HSF was primary planning format for tactics.
1 Pilot	HUD most useful for attitude and flight reference.
1 Pilot	Used HSF most. Move it up under HUD to keep head up.
1 Pilot	HUD least useful, too cluttered.
1 Pilot	PSF useful as a tracking warning.

9. What is your opinion of the Close-Look format? Does it provide adequate and useful raid assessment information? Any suggestions for change? Is it useful for targeting? Was the vertical view useful?

9 Pilots	Great, outstanding!
6 Pilots	Very useful for targetting.
3 Pilots	3-D didn't add anything.
2 Pilots	Pretty good.
1 Pilot	Good for target and threat aspect changes.
1 Pilot	Do not change a thing.
1 Pilot	Good for raid assessment.

How Change?

4 Pilots	Aircraft numbers should follow either order of original designation or order of targetting.
4 Pilots	Eliminate vertical view.
3 Pilots	Need autoscaling.
2 Pilots	Eliminate data switch; put data on full time.
2 Pilots	Didn't use vertical view, but I might if I got more used to it.
2 Pilots	Put aircraft model next to composite symbols, rather than in a data line.
2 Pilots	Add MLE.
2 Pilots	Improve redesignation.
1 Pilot	Need to indicate radar envelope in azimuth, perhaps an indication on CLF that target is about to leave coverage.
1 Pilot	Maybe color code targets' altitude bands.
1 Pilot	Don't need aircraft numbers in CLF composite symbols; put altitude there instead.
1 Pilot	Vertical view was good.
1 Pilot	Improve vertical view.
1 Pilot	Show threat Mach as well as airspeed.
1 Pilot	Show which aircraft is greatest current threat.
1 Pilot	Include broader scale.
1 Pilot	Needs rubber range.
1 Pilot	Color code enemy aircraft.
1 Pilot	Allow plan view to see all threats displayed.

10. What is your opinion of the Engine Status Format? Does the composite thrust bar provide adequate and useful information to set and monitor thrust? Any suggestions for changes?

10 Pilots	Easy to use.
1 Pilot	Amber afterburner indication bad; save amber for caution.
1 Pilot	Use words - they're easier to interpret.
1 Pilot	Thrust bars are fine.

What Change?

1 Pilot	If there is a problem, bring system display up automatically.
1 Pilot	Prefer raw engine data to composite thrust.
1 Pilot	Scale thrust to 100% at military power, then to 150% or whatever for afterburner.
1 Pilot	Show RPM as well as thrust.
1 Pilot	Eliminate thrust handle setting. Use just command and actual thrust.
1 Pilot	Eliminate command thrust. Just indicate where I am in the envelope.
1 Pilot	Show how to meet required time-over-target.
1 Pilot	Show oil and EGT full time and add numeric values for these.
1 Pilot	Engine symbols should be easier to interpret.
1 Pilot	Eliminate amber unless there's a problem.
1 Pilot	Thrust tended to move with pitch changes.

11. What is your opinion of the Stores and Countermeasures Status format? Does it provide adequate and useful information to monitor the type, number and status of stores on board? Was it useful for understanding the condition of the Countermeasures system? Does combining the two (stores and countermeasures) make sense? Any suggestions for changes?

6 Pilots	Good.
5 Pilots	Great! Don't change the format.
1 Pilot	Stores part great.
1 Pilot	Provides all the necessary information.

What Change?

2 Pilots	Make it full time on left time; share the others with CASS.
2 Pilots	Put master arm status note on a full-time format.

2 Pilots	Put chaff and flare recommendations on dedicated push-to-activate red lights in central vision.
2 Pilots	Add chaff and flare programming capability.
2 Pilots	Move chaff and flare control to stick or throttle.
2 Pilots	Automate chaff and flare dispensing.
1 Pilot	Need way of telling if the bombs are hung or not.
1 Pilot	Let pilot decide when to release chaff and flares.
1 Pilot	Keep it blue unless problem occurs.
1 Pilot	Future aircraft should have enough chaff and flares so low condition doesn't occur.
1 Pilot	Dispense indication should be on the button.

12. What is your opinion of the Electrical, Hydraulic, Fuel System Status, and Passive Sensor formats? Do they provide an appropriate level of information about system health and system problems? Any suggestions for changes?

General Comments:

5 Pilots	Good, great.
3 Pilots	Use words.
2 Pilot	They seem to work well.
2 Pilots	Tie checklists to status formats when there's a malfunction.
2 Pilots	Bring status format up automatically when there's a malfunction.
1 Pilot	Use annunciator lights, rather than the system formats.
1 Pilot	Bring these up on same display as CASS.
1 Pilot	Need to standardize colors.
1 Pilot	"Display by exception" is a good idea.
1 Pilot	Locate closer to CASS format to reduce scan.

Electrical Status:

4 Pilots	Great, the best one of the status formats.

1 Pilot	Show specific systems lost, like in the hydraulic system format.
1 Pilot	Add another page of breakers to pop.

Hydraulic Status

2 Pilots	Great.
1 Pilot	All right.
1 Pilot	Oversimplification of a complex system.
1 Pilot	Just show a list of affected actuators.

Fuel System Status

2 Pilots	Total fuel good. Didn't need the rest.
1 Pilot	Put pounds in each tank in the tank symbols to assist in CG management.
1 Pilot	Use this format to help pilot eliminate fuel-range calculations.
1 Pilot	At bingo fuel level, show route and flight profiles to landing site(s).
1 Pilot	Make joker and bingo indications more prominent.
1 Pilot	Transfer system hard to figure out.

Passive Sensor Status

4 Pilots	Didn't use it.
1 Pilot	In a real system, you would need more data.

13. What is your opinion of the Crew Alerting and Subsystem Status (CASS) format? Was it useful for monitoring fuel state and thrust? Was it adequate as a malfunction indicator? Any suggestion for change?

6 Pilots	Good, very good.
4 Pilots	Good for thrust and fuel quantity.
1 Pilot	Provides top level information.
1 Pilot	Takes too long to look at problem.

How Change?

7 Pilots	Use words, not icons, for system and impact annunciation.
1 Pilot	Put joker and bingo fuel indications in the corner of the format opposite the mission critical information.
1 Pilot	Incorporate with status; replace with system status format if there's a problem.
1 Pilot	Symbology sometimes bothersome.
1 Pilot	Add pie graph for oil pressure.
1 Pilot	Add oxygen and cabin pressure.

14. What is your general opinion of pictorial displays? What do you like best about the display formats used in this simulation? What do you like least? Would you like to have pictorial formats in a fighter of the future? For which displays?

10 Pilots	Generally, very good.
3 Pilots	HSF outstanding.
3 Pilots	Color especially useful when applied carefully.
2 Pilots	PSF in ground mode.
1 Pilot	Don't overdo pictorial. Sometimes words are better.
1 Pilot	CLF great.
1 Pilot	Situation formats best.
1 Pilot	Individual system formats best.
1 Pilot	System formats worst.
1 Pilot	HSF in air mode.
1 Pilot	The HUD wasn't as effective as an ADI would be.
1 Pilot	Add numerics.
1 Pilot	Work on PSF in air mode; it could be good.
1 Pilot	HUD least useful.
1 Pilot	HUD pathway could be simpler.
1 Pilot	Terrain depiction too simplistic.
1 Pilot	We need these formats as soon as we can get them.
1 Pilot	Great potential.

1 Pilot	Give immediate feedback.
1 Pilot	Take too much time from flying the plane.

15. In this simulation, we demonstrated the use of some cursor designation functions. what did you think of these functions? What do you think are appropriate cursor designation functions in fighter aircraft? How could they be better implemented?

7 Pilots	Put cursor control on throttles to eliminate cross coupling on flight controller.
5 Pilots	Cursor functions were good.
4 Pilots	Leave cursor on the HFS, rather than having to call it up with a button.
3 Pilots	Make cursor more prominent.
2 Pilots	Very good.
1 Pilot	Consider touch entry for cursor.
1 Pilot	Use cursor a lot more. Could replace button functions with cursor.
1 Pilot	Cursor gain too sluggish.

16. A major feature tested in this simulation is use of 3-D. It was applied to the HUD, the Perspective Situation format, the Horizontal Situation format and the Close-Look format. Did you find it useful in these formats? How could added stereo be made more useful?

8 Pilots	Not useful.
3 Pilots	Try more pronounced stereo to see if it works better.
3 Pilots	Not worth the resolution penalty.
3 Pilots	Marginally useful.
2 Pilots	Taxed the eyes; made it harder to focus on the displays.
1 Pilot	Great. Absolutely the way of the future.
1 Pilot	Not worth having yet another thing to look through.
1 Pilot	Stereo sound might help.
1 Pilot	Got a headache - nothing a couple of beers couldn't fix.

1 Pilot	Helpful only on PSF in ground mode.
1 Pilot	Only worked with Close-Look.
1 Pilot	Useful in PSF air mode and Close-Look.
1 Pilot	Not useful in HUD or HSF.
1 Pilot	Most useful in ground mode.

17. Comments not recorded elsewhere.

2 Pilots	In HUD, put "chaff" or "flares" directly, rather than "R" or "I" when missile fired at ownship.
1 Pilot	Need information like on A-6 VSI to fly realistic low level missions.
1 Pilot	Put shoot cue on lower displays as well as HUD.
1 Pilot	Put speed data in HUD to assist in making time-over-target.
1 Pilot	Need real time sensor image of target to refine and increase confidence in targeting.
1 Pilot	Need missile launch information in HUD if particular missiles require certain launch profiles.
1 Pilot	In HUD, add clock position of tracking threat as well as launching.
1 Pilot	Use "AAA", "SAM", and "AI" in HUD summary line instead of symbols.
1 Pilot	Add settable altitude warning to HUD.
1 Pilot	Put a TD box on the HUD.
1 Pilot	Replace pathway with steering box and target symbol.
1 Pilot	Include a G meter.
1 Pilot	HSF and PSF formats were excellent.
1 Pilot	Should be able to target from HSF.
1 Pilot	Need to be able to designate targets without having to spend so much time away from flying.